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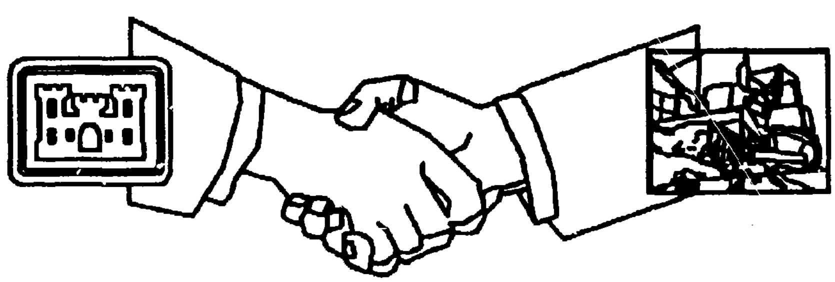
Technical Report
CPAR-GL-96-1
September 1996

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Geosynthetic Confined Pressurized Slurry (GeoCoPS): Supplemental Notes for Version 1.0

by

Dov Leshchinsky, Ora Leshchinsky



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A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs

Construction Productivity Advancement Research (CPAR) Program

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Geosynthetic Confined Pressurized Slurry (GeoCoPS): Supplemental Notes for Version 1.0

by Dov Leshchinsky, Ora Leshchinsky

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Interim report

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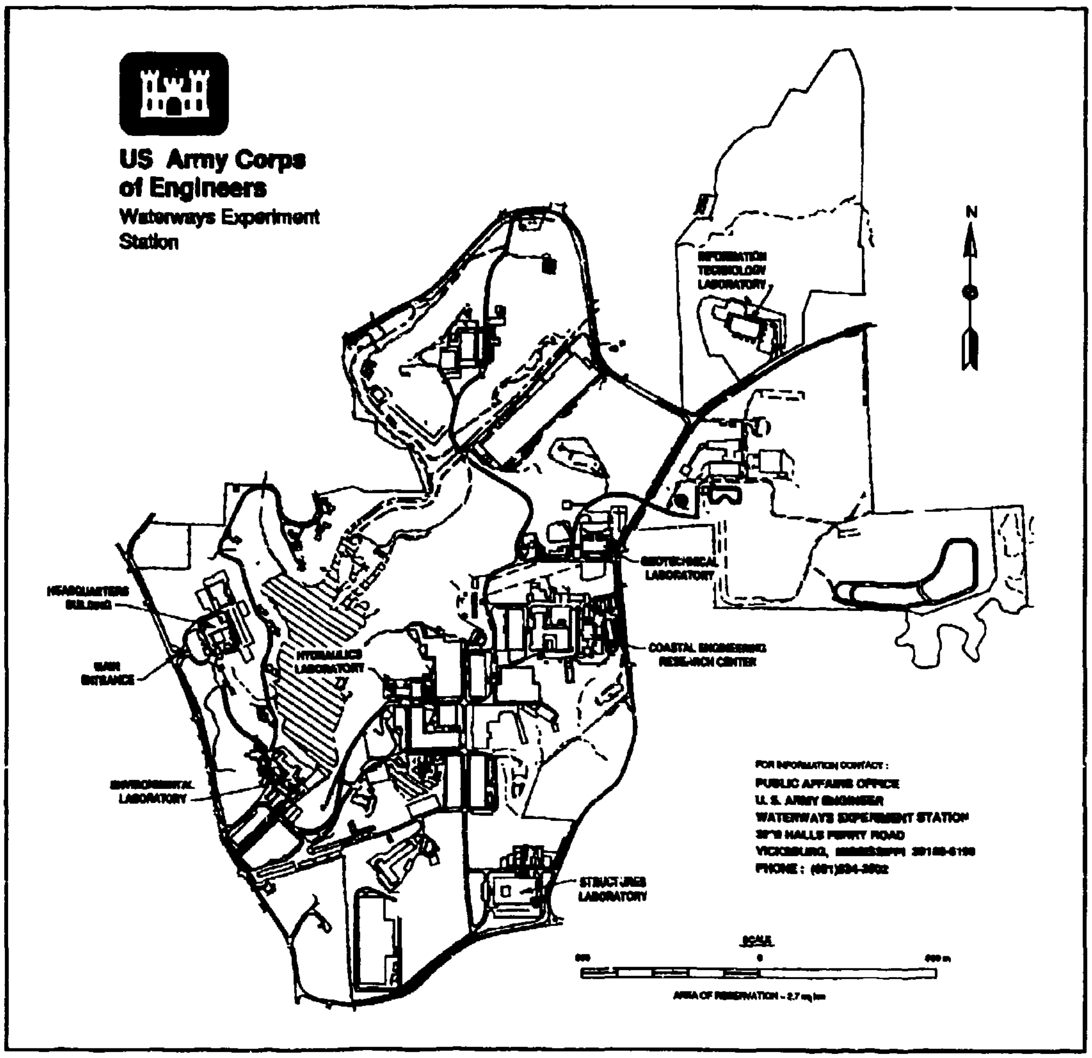

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Preface

The study reported herein was conducted by Leshchinsky, Inc., for the Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), as part of the Construction Productivity Advancement Research (CPAR) Program. The CPAR project for which the work was performed is titled, "The Development and Demonstration of Dredged Material Containment Systems Using Geotextiles," and is a collaborative effort between WES and the Nicolon Corporation, Norcross, GA. The CPAR Technical Monitors were Messrs. B. Holliday (CECW-OD) and J. Chang (CECW-EG).

The project was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL, WES; Dr. Don Banks, Chief, Soil and Rock Mechanics Division (S&RMD); and Mr. David Bennett, Chief, Soils Research Center (SRC). The WES Principal Investigator was Mr. Paul A. Gilbert (SRC), and the Nicolon Corporation investigator was Mr. Dana Toups. This report was prepared by Dr. Dov Leshchinsky and Mrs. Ora Leshchinsky. Mr. William F. McCleese was the CPAR point of contact at WES.

At the time of publication of this report, Dr. Robert W. Whalin was the Director of WES. COL Bruce K. Howard, EN, was the Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.304	meters
inches	25.4	millimeters
pounds (mass)	0.4535924	kilograms
pounds (force) per square inch	0.006894757	megapascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (force) per foot	14.5939	newtons per meter
square feet	0.09290304	square meters

1 Introduction

Background

Construction in environmentally sensitive areas (e.g., wetlands) requires using techniques causing minimum disturbance and damage. One such technique can be achieved with the aid of dikes made of geosynthetic tubes. The flat tube can be placed manually and then be filled with slurry by pumping. The quickly formed dike then may retain water on one side while allowing construction on the other. Over time, vegetation may grow over the tube's exposed surface. Tubes can also be used to contain and cap contaminated soil by forming a "working table" over very soft soil, thus allowing the construction of an embankment. Tubes filled with mortar or sand have been used to construct groins to control beach erosion. Some interesting case histories are reported by Silvester (1986), Bogossian et al. (1982), Perrier (1986), and Ockels (1991).

Tubes are made of sewn geosynthetic sheets. Inlet openings on top allow for the attachment of a pipe that transports hydraulic fill into the tube. If the fill is sandy and the geosynthetic is very pervious (e.g., geotextile), these inlets should be spaced closely (30 ft[1] apart) to ensure uniform filling of the tube. For example, flow and movement are possible only when sand particles are suspended in a sand/water mixture. If the inlets are spaced too far apart, water in the sand/water mixture will be lost by seepage through the wall of the tube, and movement of sand into the tube will stop. If clayey slurry is used, the inlets can be located as far as 500 ft apart because the fine clayey particles tend to rapidly blind the fabric, slowing down the water escape through the geotextile.

The scope of this report is limited to the design aspect of selecting a geosynthetic. Important aspects associated with actual construction can be found in Pilarczyk (1994) and Sprague (1993), for example. To ensure successful installation, construction aspects must be accounted for in the design (e.g., locations and type of inlet to tube).

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

Computer System Requirements

GeoCoPS (version 1.0) is written in FORTRAN and is compiled with Microsoft PowerStation Compiler. This compiler utilizes a 32-bit environment, using memory outside DOS domain. It achieves this by invoking a DOS extender program, called DOSXMSF.EXE, that must be present in the directory path of GeoCoPS. Results can be printed using any printer that is compatible with the system and is connected to the first parallel port (i.e., LPT1). If the printer is graphically compatible with the system through DOS, the displayed image can also be printed by using the "Print Screen" key. In this case it is recommended to first change the setup toggle within GeoCoPS to display the image in black and white. Alternatively, if the printer is HP LaserJet (or compatible), having 300 by 300 dpi, the image can be sent directly using GeoCoPS menu. Furthermore, GeoCoPS allows the user to capture the image as a PCX data file. Upon exiting GeoCoPS, the user can access this PCX file with nearly all commercially available graphics software, edit the image if necessary, and then print it using the particular software utilized.

To run properly, GeoCoPS requires at least 2MB RAM and an IBM PC-compatible system with a 386 or higher processor. It is suggested that a math co-processor be used to run the program since it is computationally intensive. The operating system should be DOS 4.00 or higher. The display screen should be a VGA or better (i.e., have 640 by 480 pixels or higher). To obtain maximum effects, a color display is recommended. For the best quality of printed output, a laser printer is recommended.

Installation of GEOCOPS

To facilitate runs, copy all files from the diskette to your hard disk (i.e., drive C) following this procedure:

1. While in DOS and in the root directory of drive C, create a dedicated directory called GEOCOPS by typing MD GEOCOPS <Enter>. <u>GEOCOPS CANNOT BE RUN FROM A DOS SHELL IN WINDOWS. IT MUST BE RUN FROM A TRUE DOS PROMPT</u>.

2. Enter this directory by typing CD GEOCOPS <Enter>.

3. Place diskette containing GEOCOPS software in drive A (or B).

4. Type COPY A:*.* <Enter> (or COPY B:*.*).

To run Program type GEOCOPS <Enter>.

2 Overview of Analysis

The formulation of a geosynthetic tube, filled with pressurized slurry or fluid, is based on the equilibrium of the geosynthetic shell. The results of this formulation provide both the circumferential tensile force in and the cylindrical geometry of the encapsulating shell material. It should be pointed out that the formulation appears in numerous articles (e.g., Liu 1981, Kazimierowicz 1994, and Carroll 1994). For the sake of completeness, only an overview of the basic formulation is reproduced hereinafter.

The following assumptions govern the formulation:

a. The problem is two-dimensional (i.e., plane strain) in nature. That is, the tube is long and all cross sections perpendicular to the long axis are identical in terms of geometry and materials.

b. The geosynthetic shell is thin and flexible and has negligible weight per unit length.

c. The material filling the tube is a slurry (i.e., a fluid); therefore, a hydrostatic state of stresses exists inside the tube.

d. No shear stresses develop between the slurry and the geosynthetic.

Refer to Figure 1 for convention and notation. For clarity of presentation, the tube considered is surrounded by air and is filled with only one type of slurry. However, extension of the formulation to include layers of slurry inside and layers of fluid outside is straightforward. In fact, GeoCoPS can accommodate two layers of slurry (each having a different density to account for slurry pumping at different times) and two layers of outside fluid (to account for the effects of partial or full submergence of the tube in water). Note that the cross section is symmetrical, having a maximum height of h at the center line, some maximum width B, and a flat base that is in contact with the foundation soil and is b wide. The pumping pressure of the slurry into the tube is p_o and its average density is γ. Hence, the hydrostatic pressure of the slurry at any depth x, as measured from point O, is $p(x) = p_o + \gamma x$.

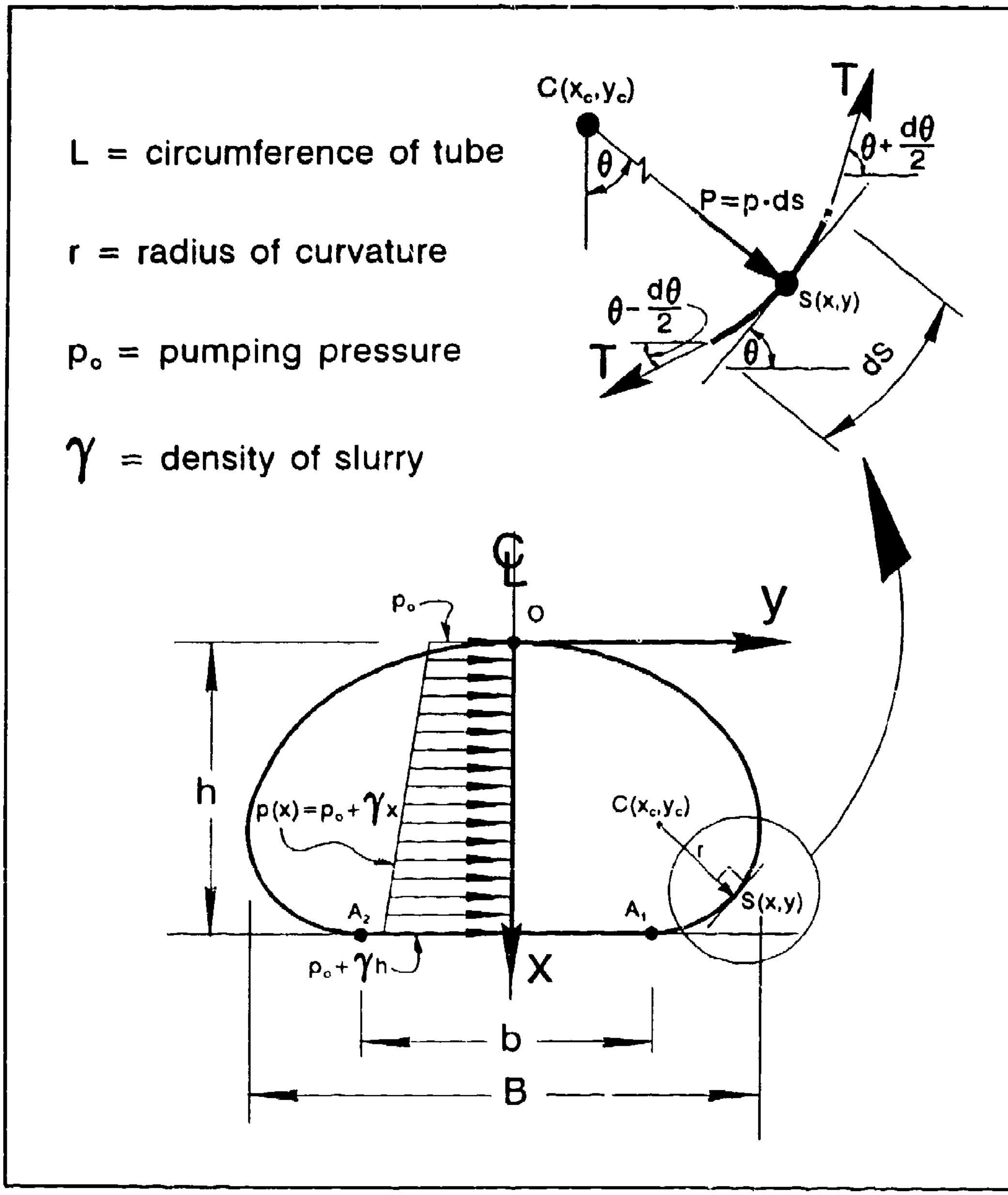

Figure 1. Cross-sectional view of geosynthetic tube: convention and notation

The geometry of the geosynthetic shell is defined by an unknown function $y = f(x)$. At a point of contact $S(x,y)$, the radius of curvature of the geosynthetic is r. The center of this curvature is at point $C(x_c, y_c)$. Note that both r and C vary along $y(x)$. Consider the forces on an infinitesimal arc length, ds, of the geosynthetic at S (see inset in Figure 1). Since it was assumed that the problem is two-dimensional and that no shear stresses develop between the slurry and the geosynthetic, it follows that the geosynthetic tensile force, T, must be constant along the circumference. Assembling the force equilibrium equation in either x or y direction leads to the following relationship:

$$r(x) = \frac{T}{p(x)} \tag{1}$$

Equation 1 is valid at any point along A_1OA_2. To simplify the analysis, it is assumed (conservatively) that the calculated T from Equation 1 is carried solely by the geosynthetic along the flat base b (i.e., no portion of T is transferred to the foundation soil due to shear along the interface between the geosynthetic and soil; this shear can be mobilized only as the geosynthetic deforms relative to the foundation). Consequently, Equation 1 expresses the complete solution for the problem. From differential calculus, the radius of curvature can be written as:

$$r(x) = \frac{\left[1 + (y')^2\right]^{3/2}}{y''} \tag{2}$$

where $y' = dy/dx$ and $y'' = d^2y/dx^2$.

Substituting Equation 2 and $p(x)$ into Equation 1 yields:

$$T \cdot y'' - (p_o + \gamma \cdot x) \cdot [1 + (y')^2]^{3/2} = 0 \tag{3}$$

Equation 3 is a nonlinear differential equation that, in general, has no closed-form solution. That is, it has to be solved numerically. Its solution produces the relationships between the geometry of the tube $y(x)$, the circumferential tensile force T, the pumping pressure p_o, the unit weight of the slurry γ, and the height of the tube h (note that x varies only between zero and h):

$$y = f(\, x \mid T \,, p_o \,, h \,, \gamma) \tag{4}$$

Since the unit weight of the slurry γ is known, Equation 4 implies that y is a function of the independent variable x and the three parameters T, p_o, and h. Typically, $y(x)$ is sought for a given (design) parameter; i.e., either T, p_o, or h is given. The other two parameters are part of the solution of the problem. Therefore, to obtain such an explicit solution, constraints must be imposed. Two such constraints will produce a solution where for a selected design parameter, the geometry of the tube, as well as the other two parameters, will be obtained. That is, two physical constraints will replace two unknown parameters that currently are part of the solution.

One constraint is the geometrical boundary condition at point O. Physically, the geosynthetic at O must be horizontal to ensure a smooth transition from one half tube of the symmetrical problem to the other half. That is

$$1 / y'(0) = 0 \tag{5}$$

The second constraint can be introduced through the specification of the flat base length b. In this case, vertical force equilibrium along b requires that

$$b = \frac{W}{p_o + \gamma \cdot h} \tag{6a}$$

where W is the weight, per unit length, of the slurry filling the entire section of the tube given by

$$W = 2\,\gamma \int_0^h y(x) \cdot dx \tag{6b}$$

Combining Equations 6a and 6b gives

$$b = \frac{2\,\gamma}{p_0 + \gamma\, h} \int_0^h y(x)\, dx \tag{7}$$

Prescribing b and simultaneously solving Equations 3, 5, and 7 for a single selected design parameter (either T, p_o, or h) will result in a tube having a certain length of circumference L. However, it is more practical to specify the circumference of a tube rather than b since the tube is manufactured from a selected number of geosynthetic sheets sewn together. If L is specified, the value of b then will be the outcome of the analysis. Hence, Equation 7 can be replaced by the following constraint:

$$L = b + \int_s ds \tag{8}$$

where ds is the arc length and, from differential calculus, is equal to $[1 + (y')^2]^{1/2} dx$

Using this definition of ds in Equation 8 combined with the substitution of Equation 7 (i.e., this equation represents the vertical force equilibrium along b) results in

$$L = \frac{2\gamma}{p_0 + \gamma h} \int_0^h y(x)\, dx + 2 \int_0^h [1 + (y')^2]^{1/2}\, dx \tag{9}$$

Now, for a prescribed L, the simultaneous solution of Equations 3, 5, and 9 yields the relationship between T, h, p_o, and $y(x)$; i.e., the explicit form of Equation 4. This solution is numerically explicit if one of the design parameters (either T, h, or p_o) is specified. The numerical process involved with such a solution is rather tedious, requiring a trial and error procedure. Several computational schemes are available in the references (e.g., Liu 1981; Kazimierowicz 1994; Carroll 1994). The procedure utilized in GeoCoPS is a modification of that proposed by Carroll (1994). For the given circumference of L and T (or h or p_o), program GeoCoPS computes the geometry of the tube $y(x)$ and the other two parameters.

Finally, there is also a practical need to assess the axial tensile force per unit length, T_{axial}, in the geosynthetic encapsulating the slurry. Refer to Figure 2 for the definition of this force. The total force P acting on a vertical plane signifying the end of a tube resulting from pressurized slurry is

$$P = 2 \cdot \int_0^h (p_0 + \gamma\, x) \cdot y(x) \cdot dx \tag{10}$$

The force P is carried by the tube in the z-direction (i.e., axial direction). The force T_{axial} per unit length then is P divided by the circumference, L, of the tube. That is

$$T_{axial} = \frac{2}{L} \int_0^h (p_0 + \gamma\, x) \cdot y(x) \cdot dx \tag{11}$$

Once the geometry of the tube has been determined through the solution of Equation 3, the value of T_{axial} can be computed by solving Equation 11.

Typically, the circumferential force T is larger than T_{axial}. Hence, if a geosynthetic having isotropic strength is considered, the value of T_{axial} is not needed in design. However, frequently, geosynthetics are anisotropic; i.e., their strength in the warp direction is different from that in the fill direction. This anisotropy is particularly common in medium- to high-strength geotextiles, where different types and numbers of yarns per unit width are used in each of the principal directions in the fabrication process. The end product may have either significantly higher or, worse, lower strength in the axial direction as compared to the circumferential direction. Consequently, to ensure the economical selection of a geosynthetic that will enable the production of a safe structure, the value of T_{axial} should always be examined and

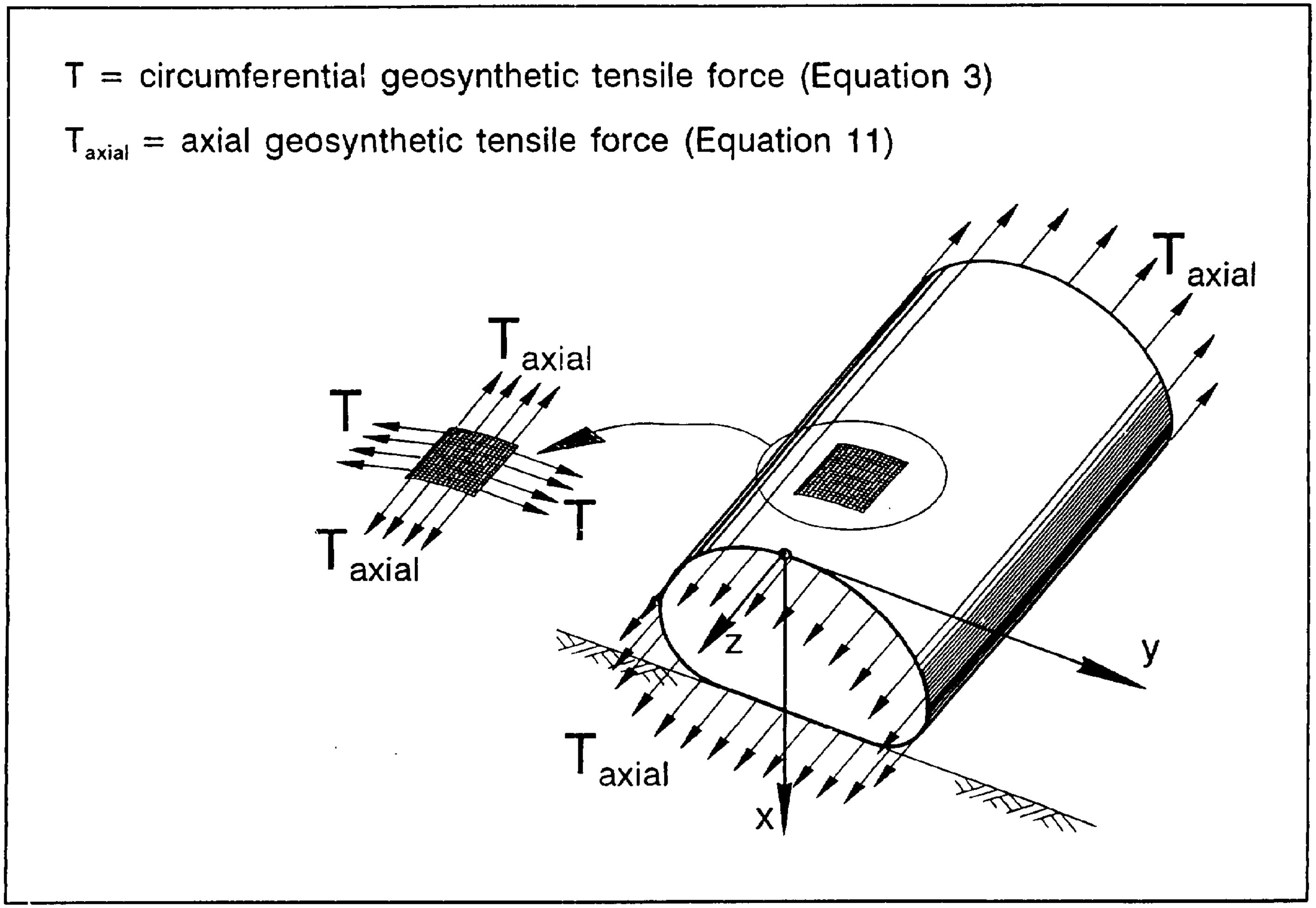

Figure 2.   Axial tensile force in geosynthetic tube

determined to be within appropriate limits for the geotextile in use. GeoCoPS provides the values of both T and T_{axial}.

3 Verification of Analysis

Numerical

Silvester (1986) presented the results of a numerical analysis in a nondimensional chart and a table for a particular circumference of a tube. It is stated that the shapes of the tube resulting from the numerical analysis have been verified experimentally. The references imply that the experimental work used for verification was conducted by Liu, some of which is reported by Liu (1981). The input data for the tabulated results were the circumference, L = 12 ft, and the pressure at the bottom of the tube (i.e., $p = p_o + \gamma \cdot h$); the unit weight of the slurry used (mortar) relative to that of water was 2.0. Table 1 shows the comparison between values calculated by Silvester (1986) and those computed using GeoCoPS for the same input data. The numerical agreement of computed results is evident in Table 1.

Liu (1981) showed the results of analysis and experimental work. Two types of slurry were used: water and mortar. One reported case was for a tube filled with mortar and submerged in water. No values of calculated T were reported. Table 2 indicates once again the very close numerical agreement.

Kazimierowicz (1994) presented an instructive numerical approach to solve the problem. Table 3 shows a comparison of results for one type of slurry and different pumping pressures. Generally, these analyses are in agreement.

These comparisons are for results obtained from different numerical procedures solving, essentially, the same governing equation (i.e., Equation 3). The closeness of results can serve as an indication that the numerical procedure utilized in GeoCoPS leads to the correct geometry and the associated tensile force (within an acceptable numerical margin of error).

Table 1
Comparison of Results Obtained from GeoCoPS and Silvester (1986) Given L, p, and $\gamma_{slurry} = 2 \cdot \gamma_w$ (See Figure 1 for notation)

Input			Calculated					
No.	L ft	p[1] p_o[2] psi	Source	h ft	b ft	B ft	Area ft²	T lb/ft
1	12.0	6.46	Silvester	3.28	1.58	4.17	11.30	1,202
		3.61	GeoCoPS	3.28	1.51	4.17	11.22	1,191
2	12.0	4.38	Silvester	2.95	2.13	4.33	10.66	693
		1.80	GeoCoPS	2.99	2.11	4.33	10.71	667
3	12.0	3.22	Silvester	2.62	2.69	4.53	10.23	397
		0.90	GeoCoPS	2.68	2.73	4.54	10.14	397
4	12.0	2.62	Silvester	2.30	3.08	4.76	9.58	286
		0.52	GeoCoPS	2.43	3.18	4.72	9.60	274
5	12.0	2.99	Silvester	1.97	3.45	4.92	8.72	194
		0.22	GeoCoPS	2.06	3.76	4.98	8.70	165
6	12.0	1.68	Silvester	1.64	3.97	5.09	7.97	139
		0.11	GeoCoPS	1.81	4.09	5.12	7.93	117

[1] p was reported by Silvester (1986).
[2] p_o was back-calculated to reproduce Silvester's same p.

Table 2
Comparison of Results Obtained from GeoCoPS and Liu (1981) Given L, p, and γ_{slurry} (See Figure 1 for notation)

Input				Calculated				
No.	L ft	p[1] p_o[2] psi	γ_{slurry} lb/cu ft	Source	h ft	b ft	B ft	d[3] ft
1[4]	3.04	0.560	62.4	Liu[5]	0.76	0.60	1.10	0.30
		0.23		GeoCoPS	0.76	0.54	1.11	0.31
2[4]	3.04	0.255	62.4	Liu[5]	0.52	1.03	1.26	0.17
		0.03		GeoCoPS	0.53	0.96	1.26	0.17
3[6]	3.41	0.498	124.8	Liu[5]	0.80	0.82	1.34	0.30
		0.21		GeoCoPS	0.81	0.80	1.36	0.30

[1] p was reported by Liu (1981).
[2] p_o was back-calculated to reproduce Liu's same p.
[3] d = height above base where maximum width of tube, B, occurs.
[4] No water outside tube.
[5] Values taken from graphical presentation.
[6] Tube is filled with mortar and is submerged in water.

Table 3
Comparison of Results Obtained from GeoCoPS and Kazimierowicz (1994) Given L, p_o, and $\gamma_{slurry} = 1.4 \cdot \gamma_w$ (See Figure 1 for notation)

Input			Calculated			
No.	L ft	p_o psi	Source	h ft	b ft	T lb/ft
1	12.0	2.53	Kazimierowicz	3.28	1.51	808
			GeoCoPS	3.29	1.51	835
2	12.0	1.95	Kazimierowicz	2.95	2.10	466
			GeoCoPS	3.00	2.12	472
3	12.0	0.66	Kazimierowicz	2.62	2.76	275
			GeoCoPS	2.70	2.69	287
4	12.0	0.44	Kazimierowicz	2.30	3.15	188
			GeoCoPS	2.52	3.05	218

Experimental

Liu (1981) conducted experiments on PVC tubes, each 8.2 ft long filled either with water or mortar. The mortar-filled tubes were submerged in water. The tubes were supported by a transparent Plexiglas foundation so that b could be measured accurately. Liu also traced the geometry of the tube. Figures 3 through 5 show the experimental results along the circumference versus the calculated geometry by GeoCoPS. Note that the three cases also correspond to the presentation in Table 2; however, in the figures the comparison is restricted to experimental data.

Clearly, the agreement between predictions and measured data is very close. This increases the confidence in the practical value of the analysis and its associated numerical procedure, thus making GeoCoPS a suitable tool for designing geosynthetic tubes subjected to slurry pressure.

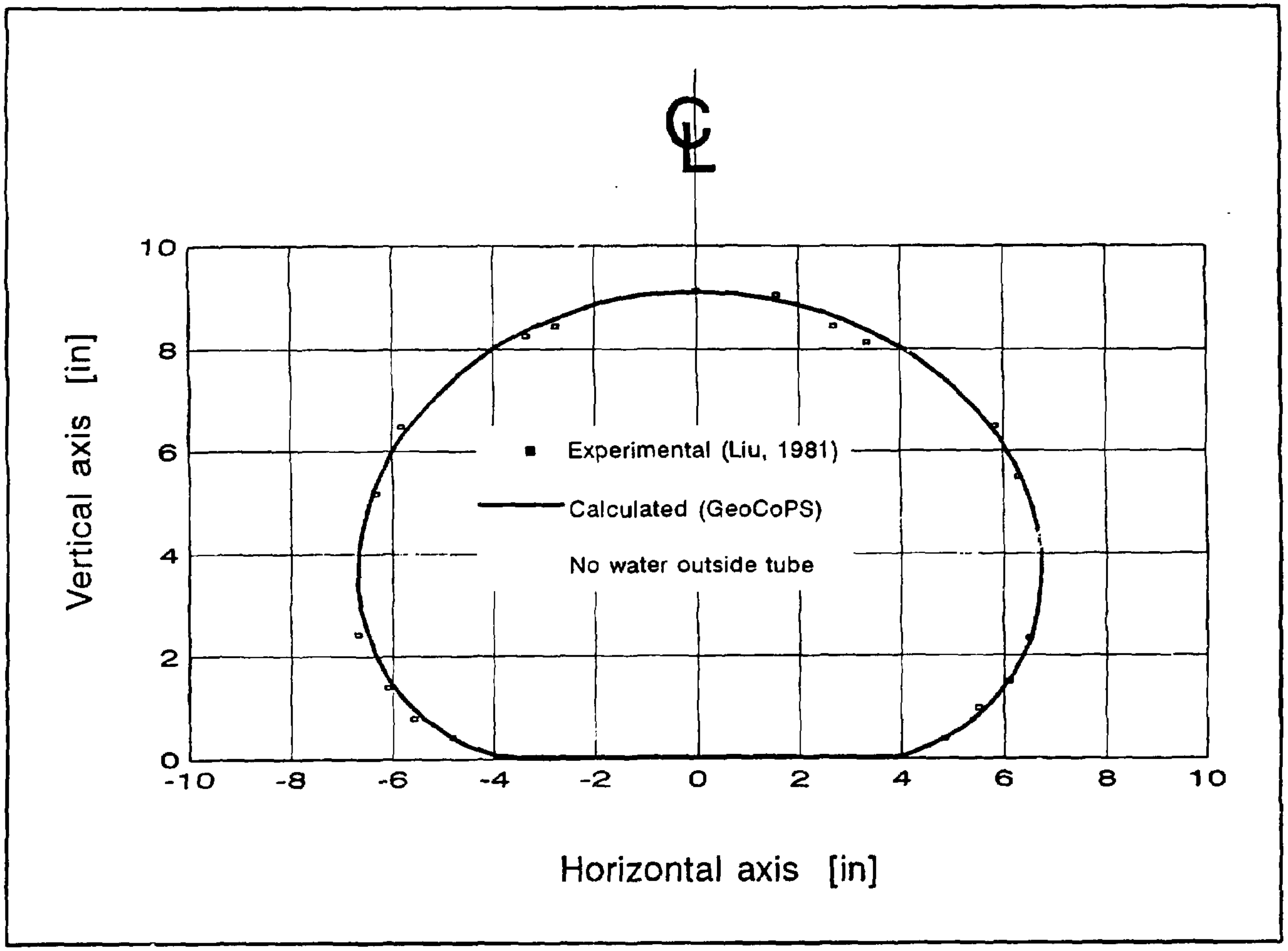

Figure 3. Experimental results (Liu 1981) versus calculated geometry by GeoCoPS (L = 3.04 ft; $p = p_o + \gamma h$ = 0.56 psi; $\gamma_{slurry} = \gamma_w$)

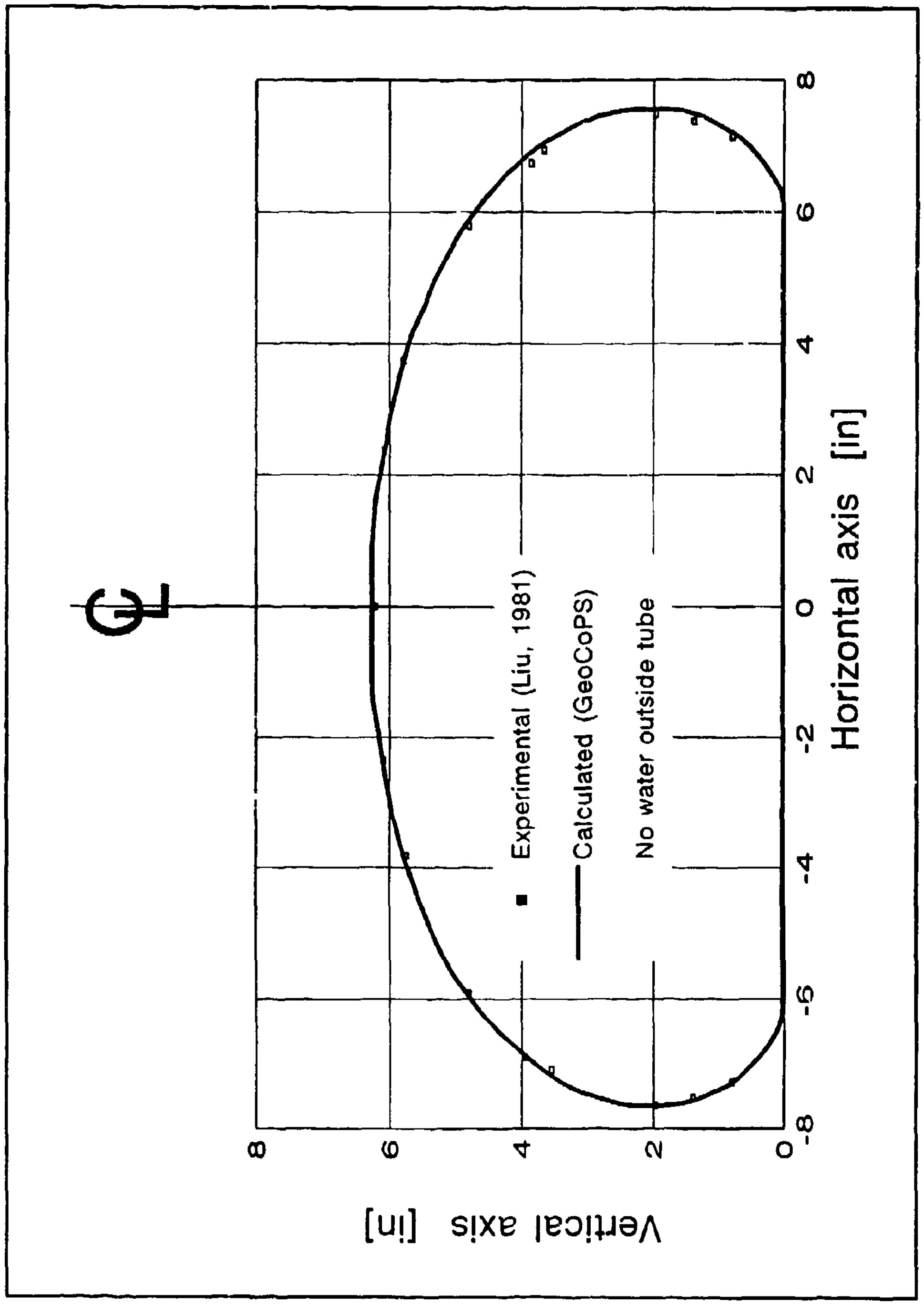

Figure 4. Experimental results (Liu 1981) versus calculated geometry by GeoCoPS (L = 3.04 ft; $p = p_o + \gamma h$ = 0.25 psi; $\gamma_{slurry} = \gamma_w$)

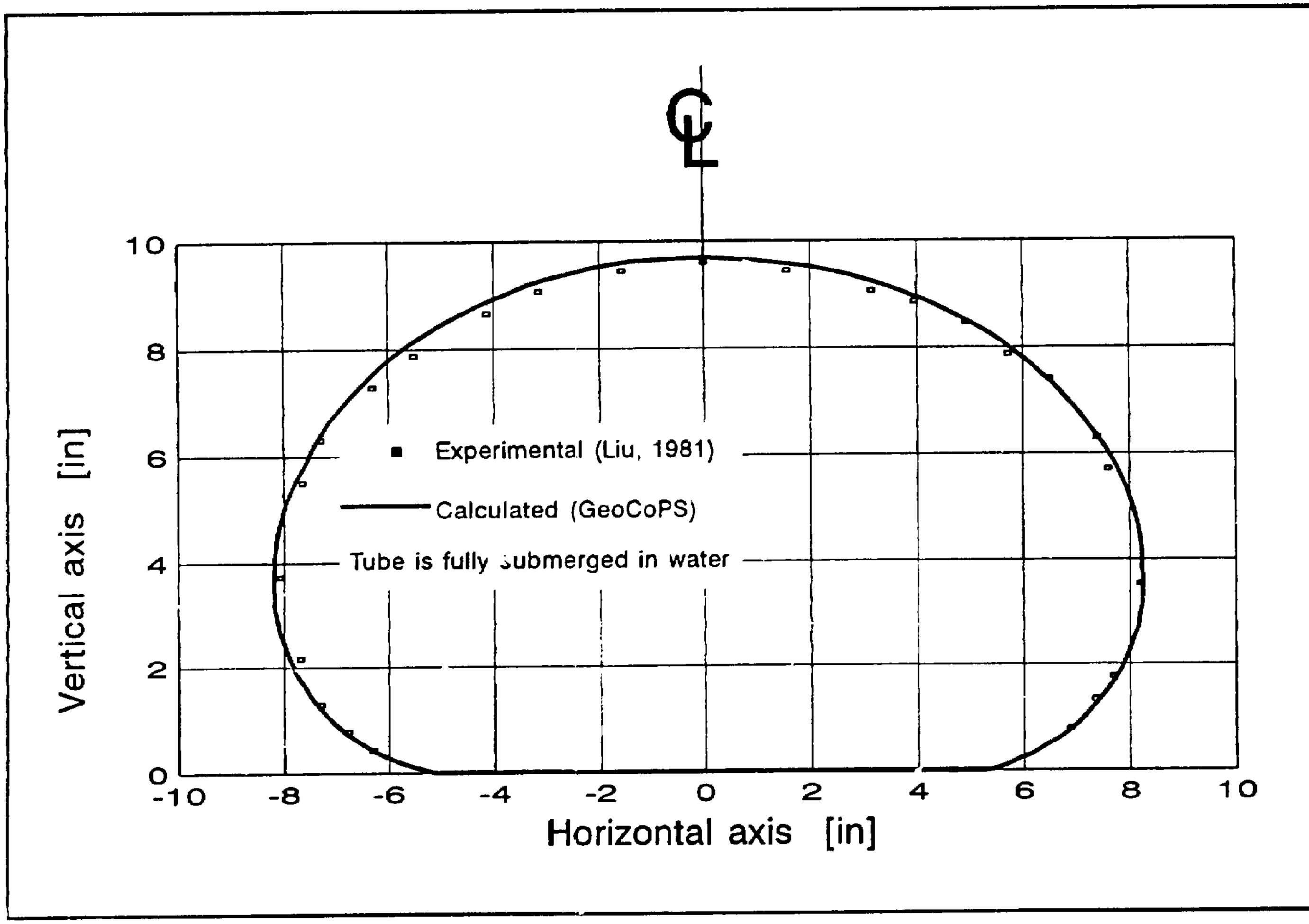

Figure 5. Experimental results (Liu 1981) versus calculated geometry by GeoCoPS (L = 3.41 ft; $p = p_o + \gamma h$ = 0.50 psi; $\gamma_{slurry} = 2 \cdot \gamma_w$)

4 Parametric Study

To realize how sensitive the solution for the geosynthetic tube is with respect to the design parameters, a parametric study was conducted. This instructive study was conducted using GeoCoPS. For all cases, the circumference of the tube was chosen as $L = 30$ ft; the unit weight of slurry relative to water was taken as 1.2. No water outside the tube was considered, and all safety factors on geosynthetic strength were set to 1.0.

Figure 6 shows the effects of the specified tensile force of the geosynthetic (circumferential strength) on the geometry of the tube. Note that to get a perfect circular cross section, having a diameter equal to $D = L/\pi = 9.55$ ft, the required T (or p_o) must approach infinity. However, at T as low as 1,000 lb/ft the height h is 6.0 ft; i.e., h is 63 percent of the maximum theoretical height, D. Increasing T to 6,000 lb/ft will produce a height of 8.5 ft or 89 percent of D. Note that there is little influence on the cross-sectional area as the height changes. This has clear design implications if storage of a certain volume of slurry is needed.

Figure 7 illustrates the effects of a designed height h on the geometry of the tube. For a desired height of 3.0 ft (about 31 percent of D), the required pumping pressure is nearly zero, and the required circumferential force is small. However, for a desired height of about 90 percent of D ($h = 8.6$ ft), the required pumping pressure is about 7.6 psi and the required circumferential force is substantially larger than before.

Figure 8 depicts the effects of the pumping pressure on the geometry of the tube. It is apparent that at low pressures, a small increase in p_o will result in a significant increase in height, h. However, beyond a certain value (e.g., 5 psi), the increase in height is insignificant, while the increase in required strength of geosynthetic is exponential.

Figure 9 demonstrates the relationship between the height of the tube and the pumping pressure. It can be seen that p_o is most significant at low pressures; as the pressure increases, its effect on h becomes negligible. In fact, the relationship approaches an asymptote of $h = D$ that will be met only when p_o is at infinity.

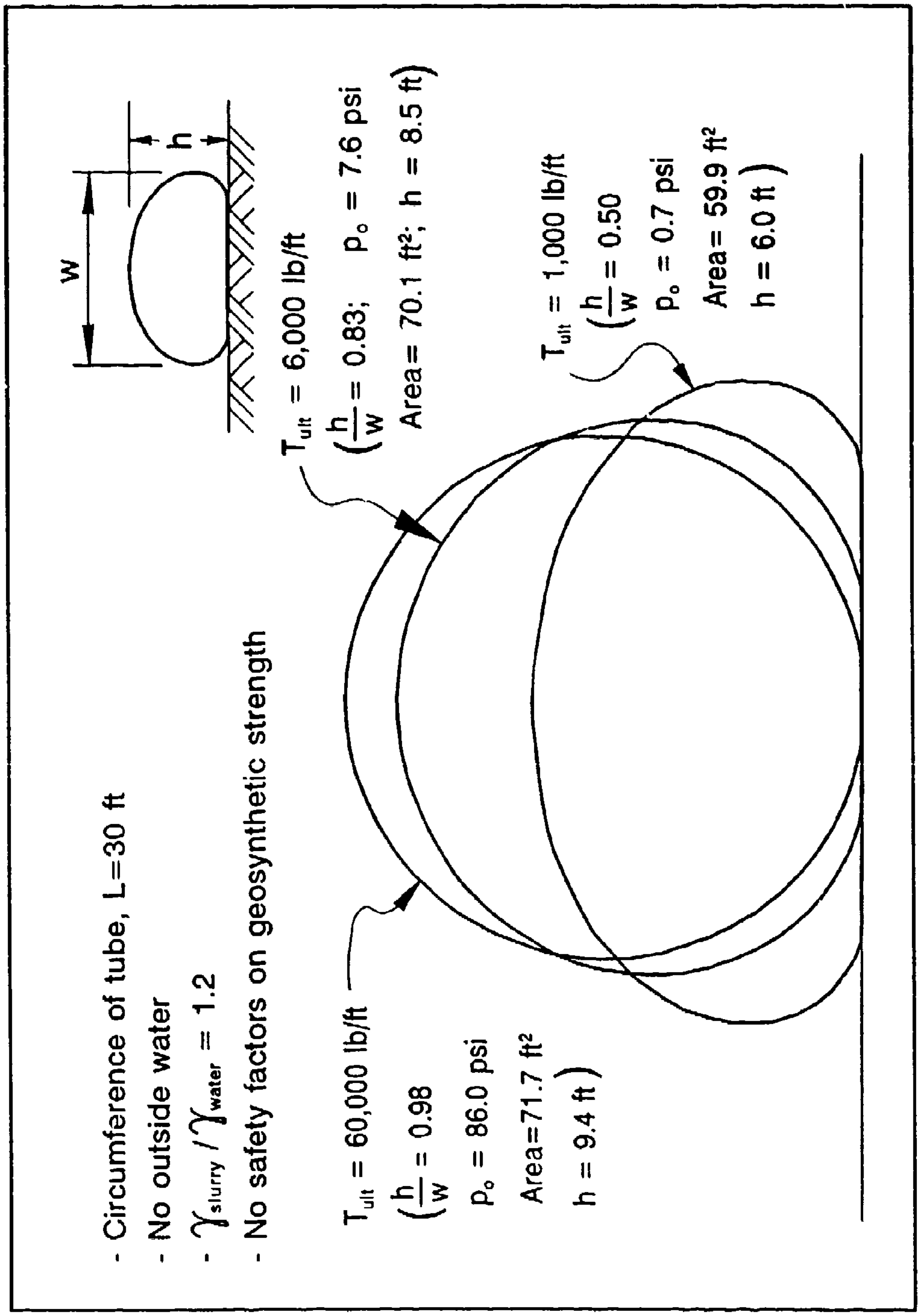

Figure 6. Effects of T_{ult} on geometry of tube

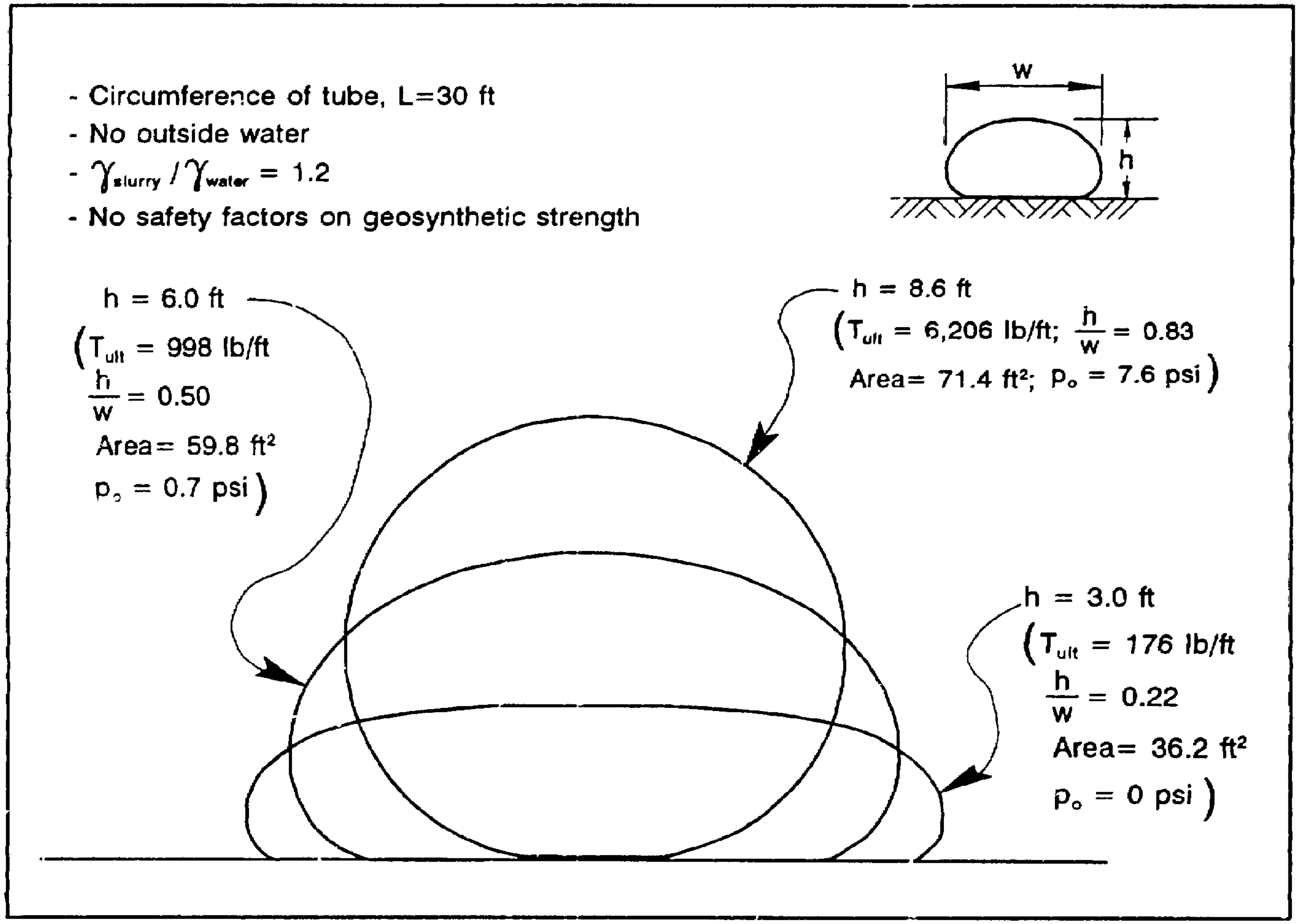

Figure 7. Effects of *h* on geometry of tube

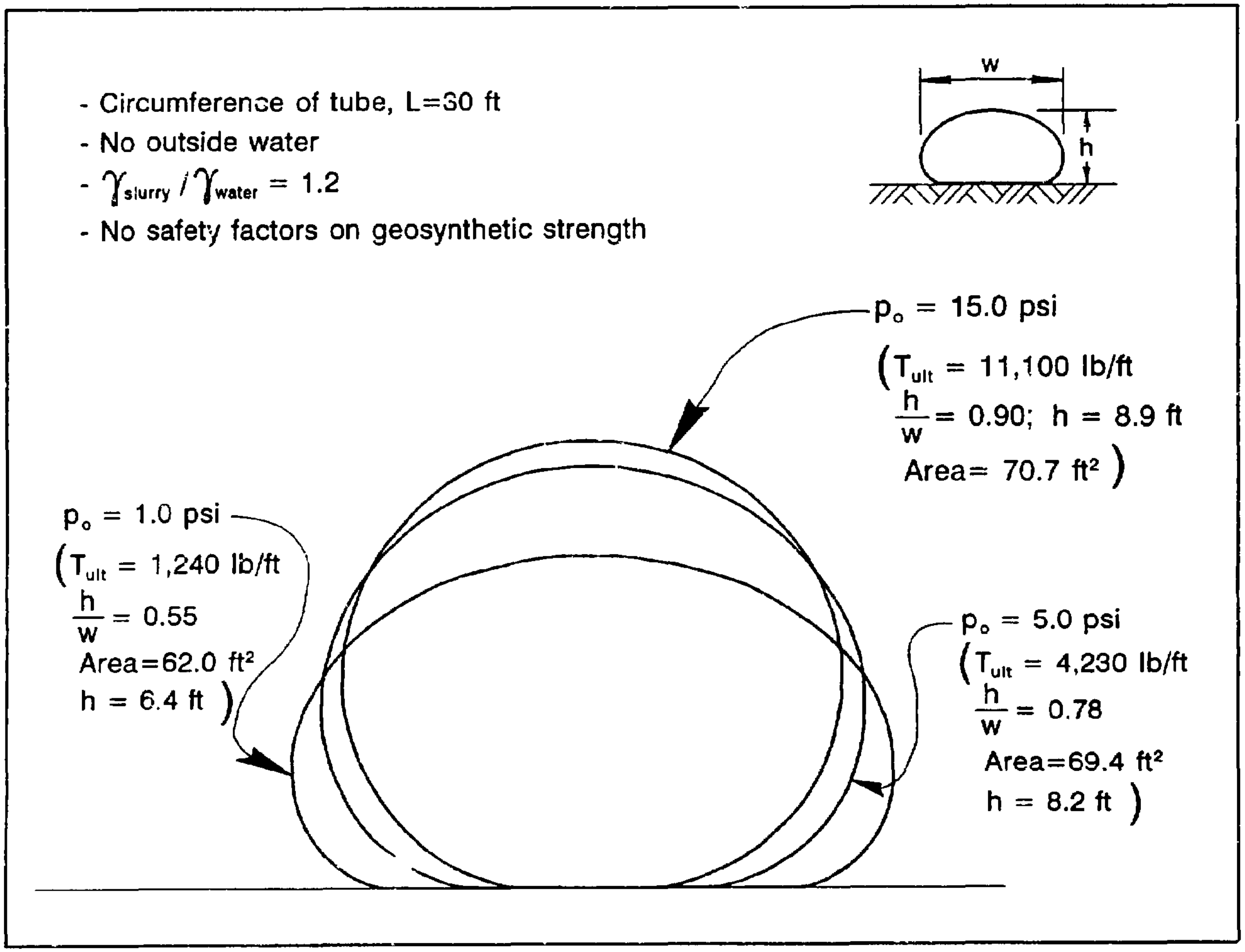

Figure 8. Effects of p_o on geometry of tube

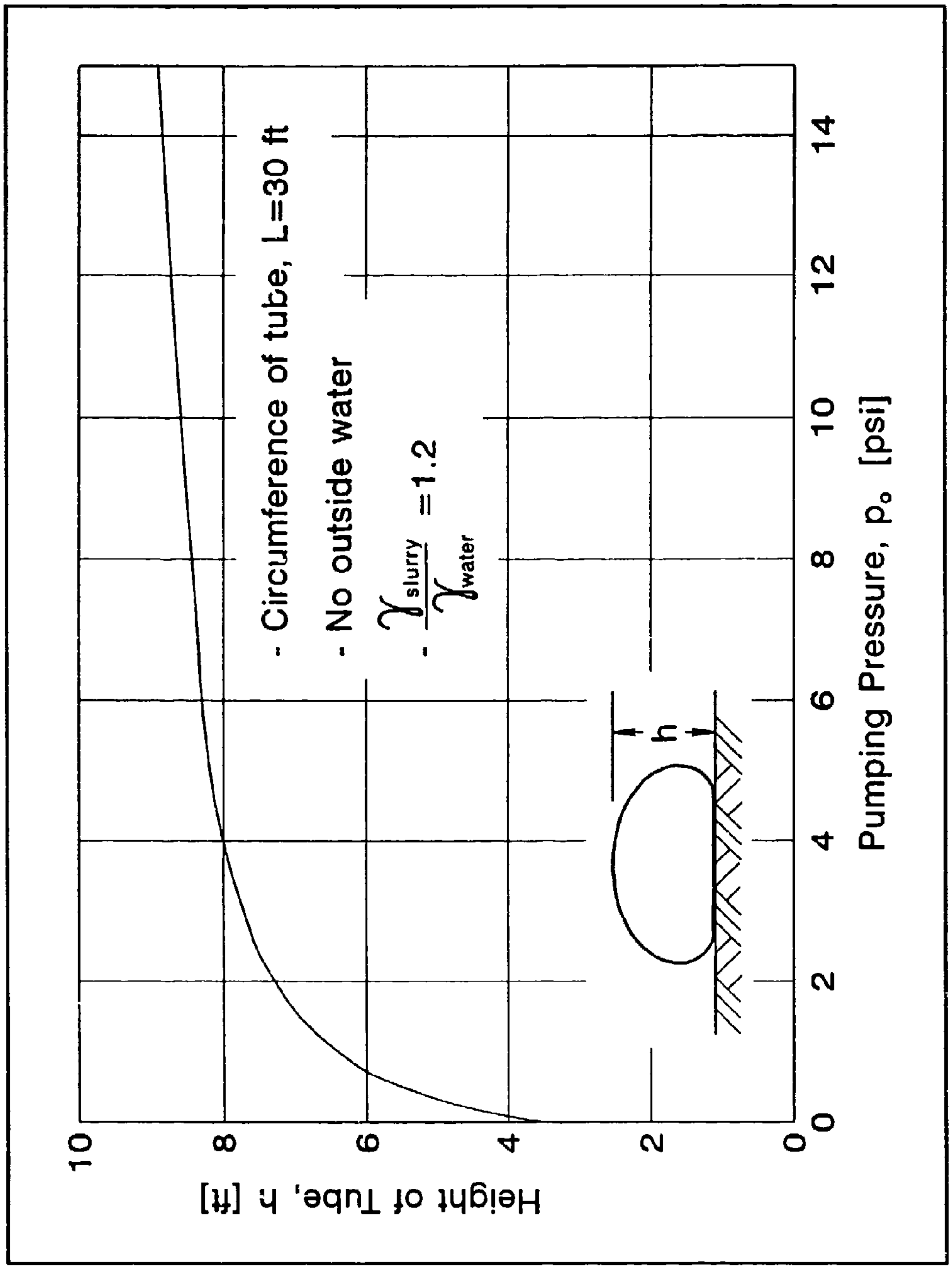

Figure 9. Height of tube versus pumping pressure

Figure 10 illustrates the effects of pumping pressure on both T and T_{axial}. For the selected parameters in the parametric study, it can be seen that as p_o decreases, the axial force approaches the value of the circumferential force. This figure is particularly instructive in the context of design; it illustrates the potential economy when selecting a geosynthetic having an anisotropic strength that corresponds to both tensile forces, T and T_{axial}, when those are significantly different.

Finally, Figures 11 and 12 show the maximum and minimum feasible heights of a tube having a given circumference L. The maximum value, h_{max}, is equal to the diameter of a tube having a circular cross section and a circumference L. The minimum feasible height, h_{min}, was calculated using GeoCoPS. It corresponds to a case where the pumping is just zero and, yet, the cross section of the tube is full. In other words, it signifies the limit for which no change in the direction of the curvature of the encapsulating tube occurs (i.e., no "sagging" of the tube occurs at its top). Such a change will render the mathematical solution of the problem of the pressurized slurry tube invalid. Physically, it implies that the tube section is not full, making the specified circumference irrelevant (i.e., too long). Figures 11 and 12 indicate the range of feasible heights for given circumferences. Note that when the tube is not submerged (Figure 11), the slurry density has negligible effects on h_{min}. However, full submergence (Figure 12) produces some limited effects on the minimum height. Also, h_{min} for the submerged tube is higher than for the nonsubmerged one. This is a result of a reduction in effective stresses within the slurry as the tube becomes submerged. Reduced slurry stresses allow the tube to maintain a cross section that is close to a circle.

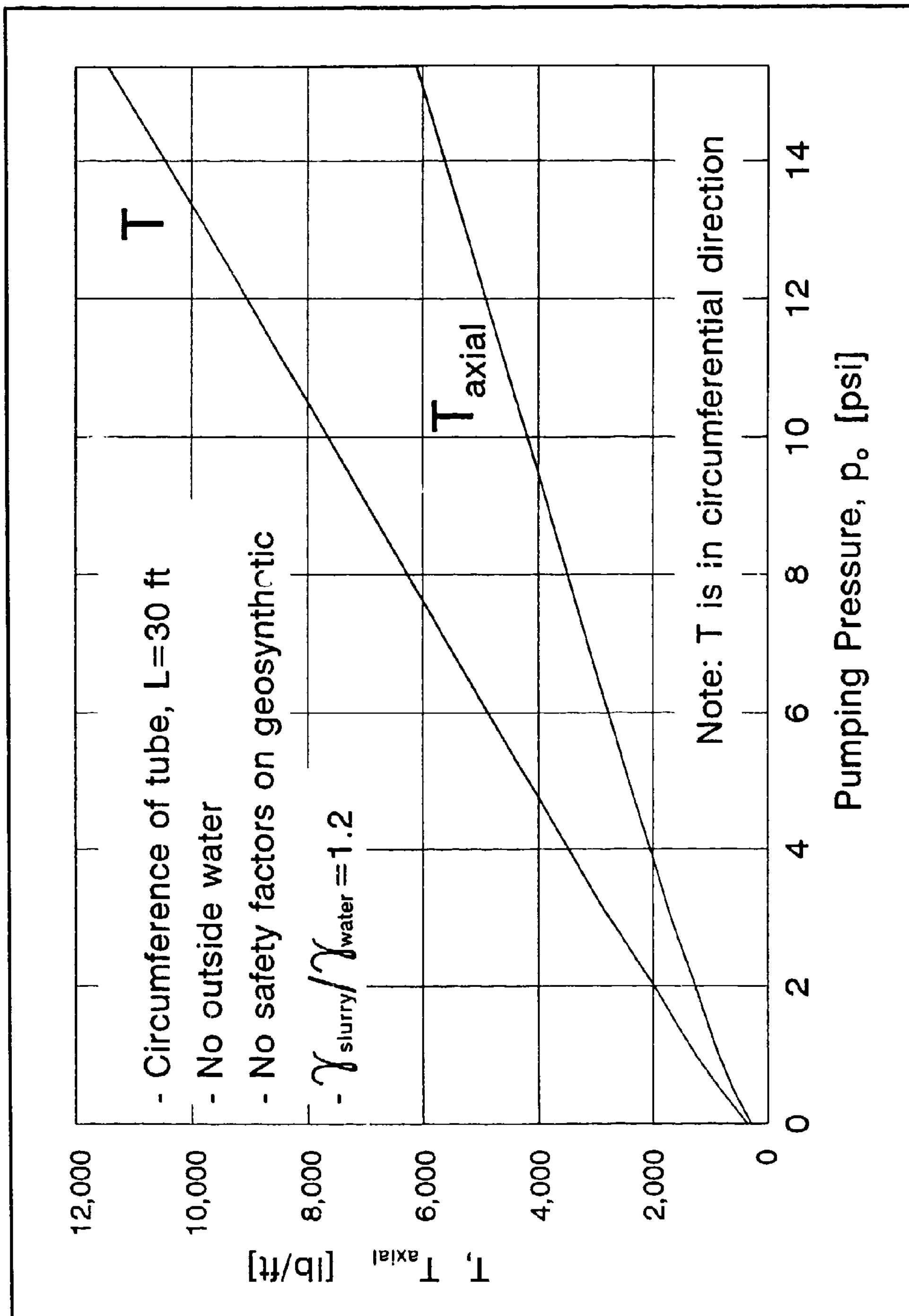

Figure 10. T and T_{axial} versus pumping pressure

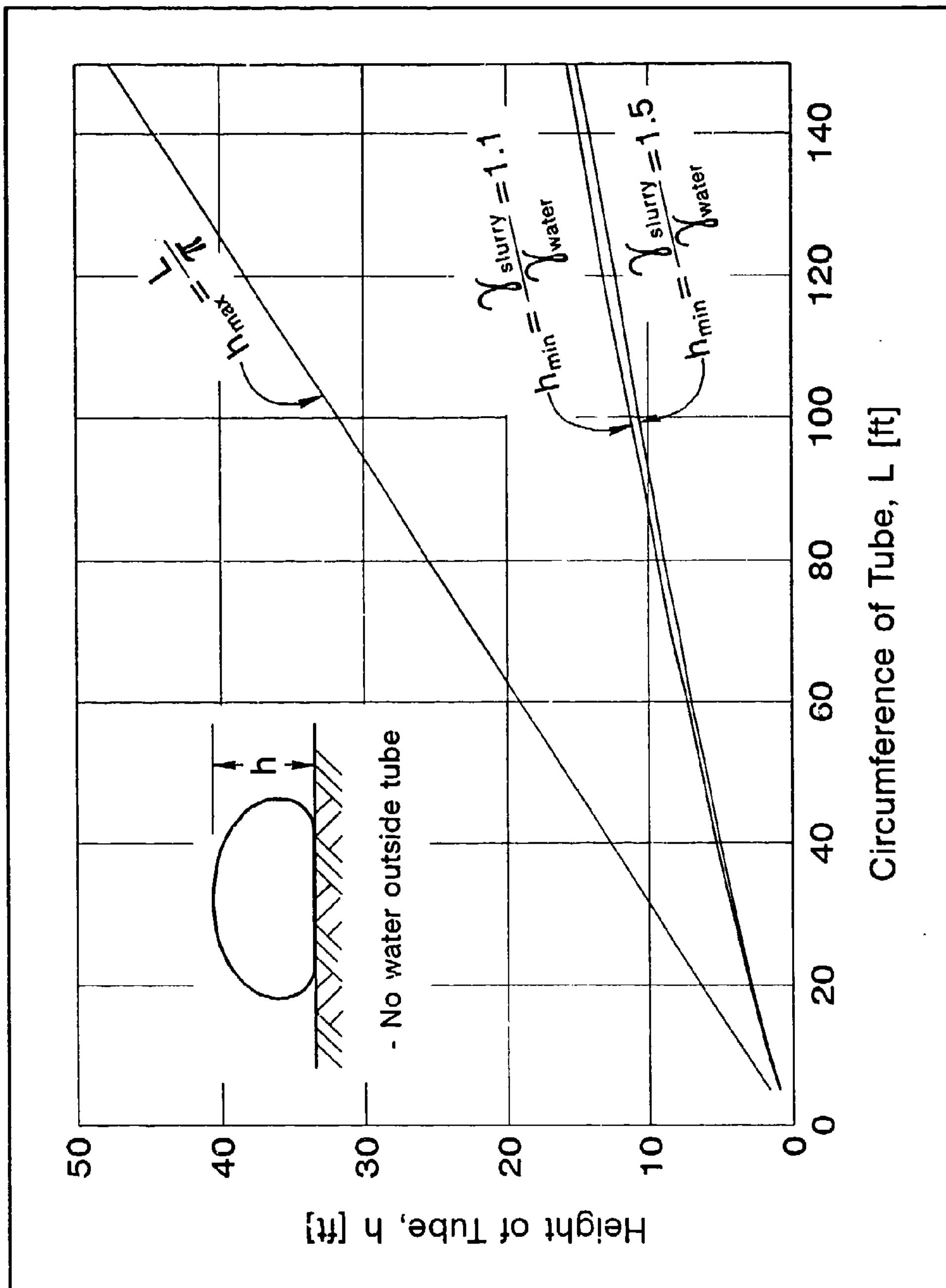

Figure 11. Extreme values of feasible heights of tube (no water outside tube)

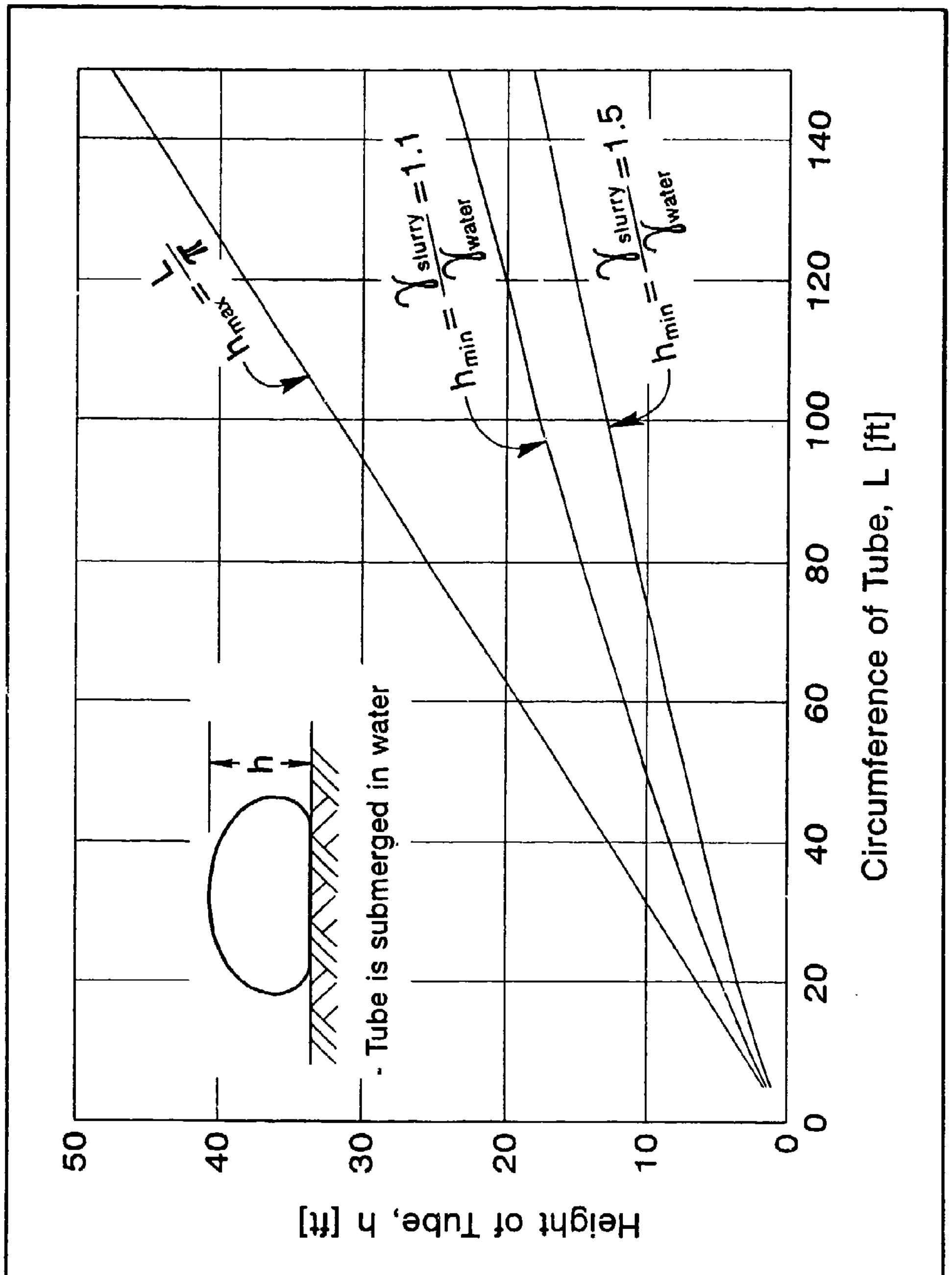

Figure 12. Extreme values of feasible heights of tube (tube is submerged in water)

5 Design Considerations

Geosynthetic Strength

The analysis in Chapter 2 renders the circumferential and axial force in the geosynthetic at working load conditions. However, to select a geosynthetic possessing adequate ultimate strength, safety factors should be applied to either calculated force. Current practice utilizes partial safety factors (e.g., Koerner 1994). It is recommended to use the following partial safety factors:

$$T_{ult} = T_{work} \cdot (F_{s-id} \cdot F_{s-cd} \cdot F_{s-bd} \cdot F_{s-cr} \cdot F_{s-ss}) \tag{12}$$

where

T_{work} = the calculated tensile force in the geosynthetic at working load conditions, either in the circumferential direction ($T_{work} = T$) or in the axial direction ($T_{work} = T_{axial}$).

F_{s-id} = factor of safety for installation damage. In the context of tubes, this factor refers to an accidental increase of pumping pressure. Such an increase is possible since accurate control of the pressure in the field is quite difficult to maintain. This increase may cause a local rupture of the seam or of the geosynthetic in the vicinity of the seam. A preliminary minimal value of $F_{s-id} = 1.3$ is recommended.

F_{s-cd} = factor of safety for chemical degradation. For a typical slurry, most geosynthetics are inert. To verify whether a slurry may cause damage, the test specified in American Society for Testing and Materials (ASTM) D 5322-92 (ASTM 1995a) can be used as a guidance. However, to make the test meaningful, the actual slurry should be used. Furthermore, chemical degradation can be caused externally by a direct exposure to the sun (ultraviolet radiation (UV)). To assess the tendency for such degradation, the test procedure specified in ASTM D 4355-92 (ASTM 1995c), can be used. Assuming that the geosynthetic is indeed inert and that the strength of the portions exposed to the sun is needed only during construction (and shortly after as the slurry solidifies), a minimum preliminary value of $F_{s\text{-}ed} = 1.0$ is recommended. It should be pointed out that most geosynthetics contain carbon black and, therefore, deteriorate slowly (typically years) when exposed to UV.

$F_{s\text{-}bd}$ = factor of safety for biological degradation. Such degradation does not seem to be a problem in most cases where tubes are used; therefore, a preliminary value of $F_{s\text{-}bd} = 1.0$ is recommended. However, this factor is left as part of Equation 12 to allow for its inclusion, if deemed necessary.

$F_{s\text{-}cr}$ = factor of safety of creep. It signifies the required reduction of the ultimate strength so that at the end of the designed life of the structure, the deformations will be tolerable. The creep behavior of a geosynthetic can be determined using the test specified in ASTM D 5262-92 (ASTM 1995c). However, this factor should be evaluated in the context of tubes; that is, maximum tensile force in the geosynthetic will be mobilized during pumping. After pumping, as the slurry solidifies, this force decreases. Consequently, this maximum force will exist over a short period of time; therefore, a relatively small creep safety factor can be assigned. Its value must assure that the tensile creep rupture strength (see ASTM D 5262-92 for definition) will be larger than T_{work} during the time this force exists (i.e., during pumping and shortly after, as the excess pore-water pressure dissipates and the slurry solidifies). A minimum preliminary value of $F_{s\text{-}cr} = 1.5$ is recommended.

$F_{s\text{-}ss}$ = factor of safety for seam strength. Seam efficiency may be quite low for high-strength woven geotextiles. A minimum preliminary value of 2.0 is recommended. The exact value should be determined using the test specified in ASTM D 4884-90 (ASTM 1995g); i.e., this test provides the seam efficiency, and $F_{s\text{-}ss}$ is, by definition, equal to 1/(seam efficiency).

T_{ult} is the ultimate strength of the required geosynthetic. Note that its value should be in the circumferential direction if $T_{work} = T$ is used in Equation 12. If $T_{work} = T_{axial}$ is used, then T_{ult} is in the axial direction. A geosynthetic possessing at least these ultimate strengths in its warp and fill directions, with correspondence to the circumferential and axial directions, should be specified. The ultimate strength should correspond to the test specified in ASTM D 4595-94 (ASTM 1995h).

Geosynthetic Retention of Solid Particles

Typically, the geosynthetic encapsulating the slurry has to function also as a filter allowing the fluid transporting the solids into the tube to drain out while retaining the solid particles (i.e., perform as a cheesecloth). As is the usual case with filters, the geosynthetic must possess two required properties that are opposite each other: be pervious and, simultaneously, have a "perfect" retention of solids. This perfect retention is particularly important in case contaminated soil is to be contained by the tube.

Using the geosynthetic to retain the solid particles in the slurry necessitates compatibility between it and the solids in the slurry. Using ASTM D 4751-93 (ASTM 1995d) gives the apparent opening size (AOS) of the geosynthetic. AOS (or O_{95}) indicates the approximate largest solid particle that would effectively pass through the geosynthetic. Koerner (1994) provides an instructive table showing different design methods to ensure the retention of a soil having a particular grain size distribution considering a given AOS. The method recommended here was developed by Task Force No. 25, American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 1990):

a. For soil with $\leq$ 50 percent passing sieve No. 200: $O_{95} < 0.59$ mm (i.e., AOS $\geq$ sieve No. 30).

b. For soil with > 50 percent passing sieve No. 200: $O_{95} < 0.30$ mm (i.e., AOS $\geq$ sieve No. 50)

Consequently, upon using conventional tests to determine the distribution of grain size of the slurry, one can specify the maximum allowed AOS of a geosynthetic. It should be noted that when the slurry is composed of clayey soils, experience indicates that the geosynthetic openings tend to stop the passage of particles rapidly while allowing for water to seep clean outside (Leshchinsky 1992). In the case of contaminated slurry, however, the AOS criteria may have to be modified to ensure a truly perfect retention. Such modification can be done through experiments simulating the in situ conditions.

Using the onsite slurry, one can evaluate whether the selected geosynthetic will not clog. This performance feature can be determined using ASTM D 5101-90 (ASTM 1995f). Typically, clogging should not be a problem if the AOS criteria were utilized in selecting a geosynthetic. If, however, the slurry may create a biological activity on the geosynthetic, the clogging potential then can be evaluated using ASTM D 1987-91 (ASTM 1995b). Biological activity is typically a long-term issue, whereas the filtration capacity in a tube is usually a short-term (a few months) issue.

It is quite possible that the conflicting requirements of perfect particle retention and high permeability, combined with a required high-strength material, will result in a geotextile that is not available. In this case, a nonwoven geotextile can be used as a liner to retain the fine particle. The outside geosynthetic can then be a high-strength woven (and very pervious) geotextile. This combination will produce an acceptable encapsulating material.

Consolidated Height of Tube

After the pumping and as the slurry consolidates (i.e., solidifies), the height of the tube drops while its maximum width increases very little. The drop in height can be very significant, especially when fine soil slurry is pumped in. The following approximate procedure allows for an estimate of the average drop in height once a certain density of the fill material is achieved.

Assuming the solidified slurry is fully saturated (S = 100 percent) and using basic volume-weight relationships, it can be shown that

$$\omega_o = \frac{G_s - \dfrac{\gamma_{slurry}}{\gamma_w}}{G_s\left(\dfrac{\gamma_{slurry}}{\gamma_w} - 1\right)} \tag{13}$$

and

$$\omega_f = \frac{G_s - \dfrac{\gamma_{soil}}{\gamma_w}}{G_s\left(\dfrac{\gamma_{soil}}{\gamma_w} - 1\right)} \tag{14}$$

where

ω_o and ω_f = the initial and final water content of the fill material, respectively

G_s = the specific gravity of solids (constant for same soil particles, regardless of change in water content)

γ_{soil}, γ_{slurry}, and γ_w = the unit weights of the soil (solidified slurry), slurry, and water, respectively

Assuming the consolidating material is moving only downwards (i.e., one-dimensional movement; negligible lateral movement) and making use of the relationship $[\Delta e/(1 + e_o)] = \Delta h/h_o$, the following equation is obtained:

$$\frac{\Delta h}{h_o} = \frac{G_s \left(\omega_o - \omega_f\right)}{1 + \omega_o G_s} \quad (15)$$

where Δh and h_o are the decrease in the height of the tube and the initial height of the tube, respectively, and e is the void ratio.

Combining Equations 13, 14, and 15, one can estimate the drop in the height of the tube as the material inside densifies. Figure 13 illustrates the result of combining these equations, assuming $G_s = 2.70$. Note, for example, that when a slurry having $(\gamma_{slurry}/\gamma_w) = 1.1$ consolidates to $(\gamma_{soil}/\gamma_w) = 1.2$ (i.e., 9 percent increase in density), the resulting decrease in height is about 50 percent. Experience indicates that when fine-grained material is pumped in, the tube will drop about 50 percent in height within about a month (Leshchinsky 1992). At this stage, a solid soil is formed over which a person can walk. If the objective is to form a tube of a certain desired height, then additional slurry can be pumped in. (GeoCoPS can handle two slurry densities inside the tube.) This process can be repeated until the final desired height is attained. Alternatively, pumping sand (or soil with more than 50 percent of the particles greater than sieve No. 200) will result in final tube dimensions acceptable typically after only one pumping.

In the strict sense of soil mechanics, Equation 13 should account for salt content in the slurry, if relevant. Although salinity has some effects on the calculated water content, especially of clayey slurry, the end result with regard to height change (Equation 15) is negligible. That is, the difference in height decrease due to the inclusion of salinity in the calculations is only a few percent. Consequently, it is recommended to simplify the problem and ignore salinity in conjunction with Equation 15.

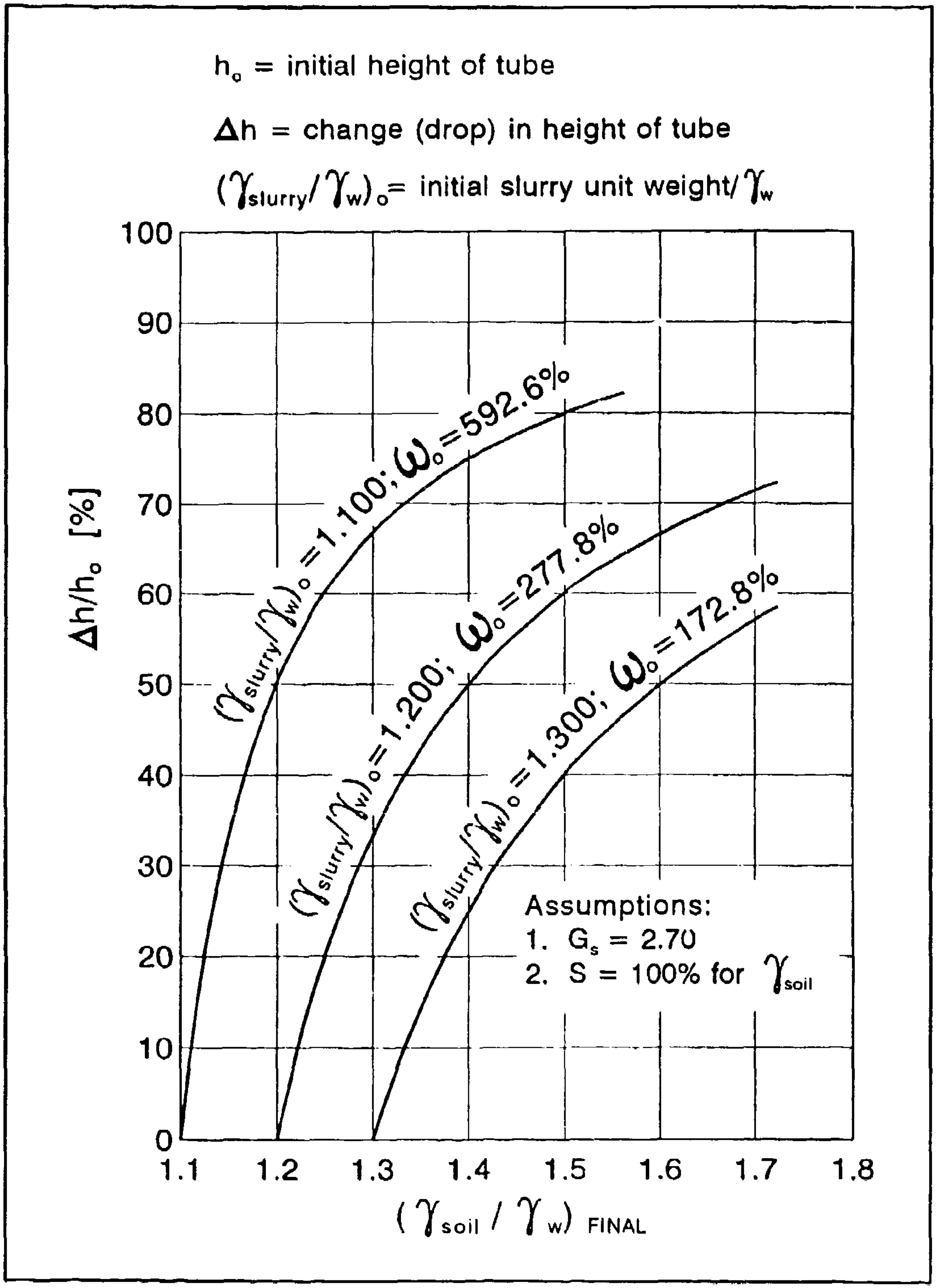

Figure 13. Drop in height of tube as function of density of soil

6 Examples Using GeoCoPS

Figure 14 shows the notation used in GeoCoPS. As seen, two different slurries can be specified. Also, outside liquid (typically water) may be present, partially or fully submerging the tube. Figure 15 illustrates the options available in GeoCoPS. While in the program, the user can invoke the "help" command. In response, either a concise descriptive text or a graphical illustration will appear.

The following pages in this chapter are the direct printout of GeoCoPS resulting from the run of three different example problems. Example 1 utilizes the option to find the geometry of the tube and the pumping pressure for given circumference L and geosynthetic ultimate strength, T_{ult}, in the circumferential direction. Two slurry densities are specified; the outside water is 5 ft high, 2 ft lower than the bottom (and heavier) slurry layer. Note that although the circumference was specified as 80.0 ft (signifying, for example, five geotextile sheets, each having an effective width of 16 ft, sewn together), the results converged to a circumference of 80.7 ft. This is well within the allowable numerical tolerance set in GeoCoPS. (Refer to the equations presented in Chapter 2 to realize that a numerical process of finite accuracy must be used for numerical evaluation.) The printout of results and Figure 16 show that the pumping pressure is only 0.5 psi. Note that the cross-sectional area of each of the two slurries is also printed. This area signifies the volume of slurry per foot length of the tube. Hence, for a given tube length, its storage capacity can be evaluated. Also, note that the required geosynthetic strength in the axial direction is quite high (about 77 percent of the circumferential one) implying that for this problem, a geosynthetic with an isotropic strength (i.e., a fabric having the same strength in its warp and fill direction) will likely be the most practical to specify.

Example 2 is for a case where the circumference and desired height of the tube are given as 30.0 and 8.0 ft, respectively; the results, however, converged to a numerically acceptable closeness of 30.6 and 7.9 ft. A uniform slurry and an unsubmerged tube are considered. See Figure 17 for the calculated cross section. Note that the required axial strength is about 58 percent of the circumferential one. The required circumferential strength is also rather large. Hence, there exists an economic incentive to specify an

Restrictions:

1. Density of upper slurry layer is less than or equal to that of lower.
2. Density of outside upper liquid is less than or equal to that of lower fluid.
3. Density of either lower or upper liquid is less than or equal to that of upper slurry layer.

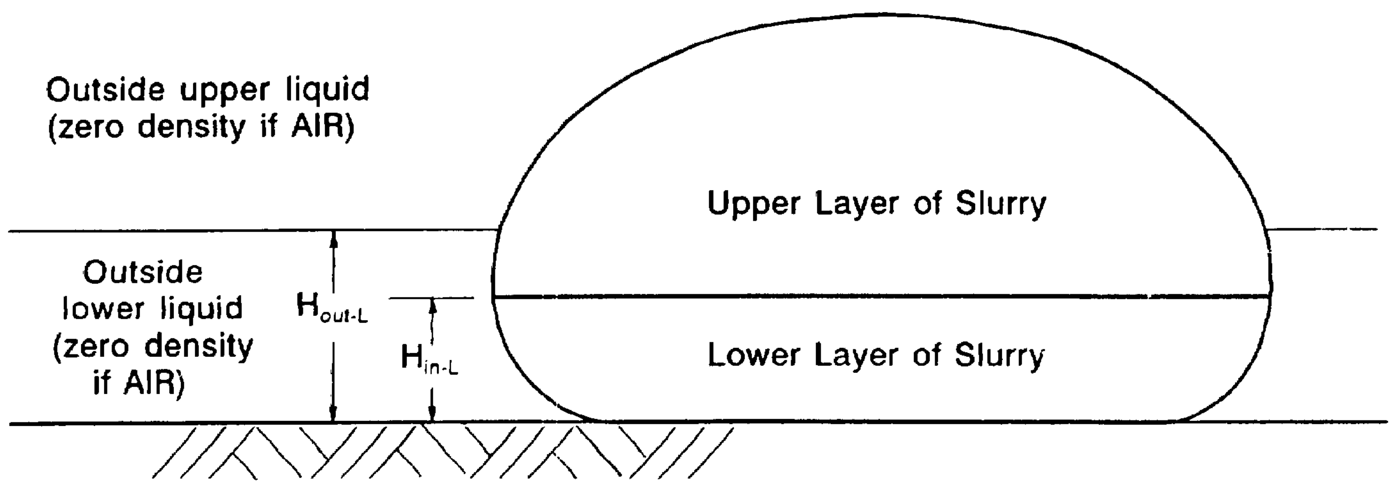

Figure 14. Notation used in GeoCoPS

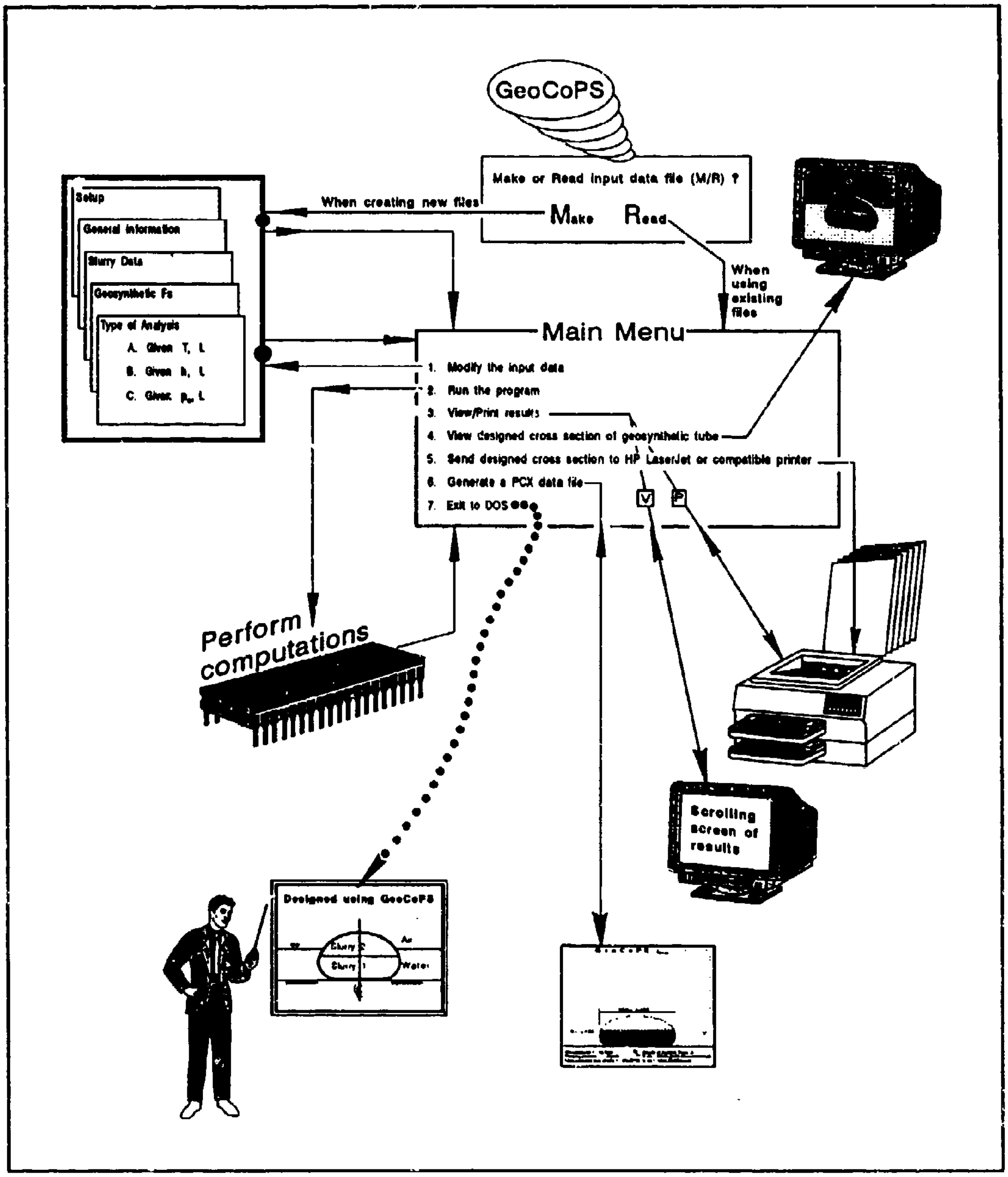

Figure 15. Schematic diagram showing options in GeoCoPS

GeoCoPS

Version 1.0

Geosynthetic Confined Pressurized Slurry

Project Title:	Example 1
Project Number:	N/A
Project Designer:	N/A
Description:	Given the circumference of the tube and the geosynthetic strength, find the geometry of the tube as well as the pumping pressure.

Input File Name:	EXAMPLE1.IN
Output File Name:	EXAMPLE1.OUT
Date:	08/27/95
Time:	14:24:56

Input data file: EXAMPLE1.IN Date printed: 08/27/95 Time printed: 14:24:56

G e o C o P S Version 1.0
Geosynthetic Confined Pressurized Slurry

Project title:	Example 1
Project No.:	N/A
Project designer:	N/A
Project description:	Given the circumference of the tube and the geosynthetic strength, find the geometry of the tube as well as the pumping pressure.

D A T A

Density of Slurry/Density of Water:	1. Lower layer . . .	1.3	
	2. Upper layer . . .	1.1	
Density of outside liquid/Density of Water:	1. Lower layer . . .	1.0	
	2. Upper layer . . .	.0	
Specified height of lower layer of slurry, Hin-L		7.0	ft
Specified height of outside lower layer of liquid, Hout-L		5.0	ft
Specified safety factors for geosynthetic:			
1. Installation damage, Fs-id		1.3	
2. Chemical degradation, Fs-ch		1.0	
3. Biological degradation, Fs-bd		1.0	
4. Creep, Fs-cr		1.5	
5. Seam strength, Fs-ss		2.0	

Requested type of analysis: 'A' - solve the problem for a circumference of 80.0 ft and ULTIMATE strength of a geosynthetic of 12,000 lb/ft

R E S U L T S

Results are for a solution converging to a circumference of tube of 80.7 ft and ULTIMATE geosynthetic strength of 12,000 lb/ft

Geosynthetic in CIRCUMFERENTIAL direction:		
Tensile force at WORKING conditions	3,077.0	lb/ft
Required ULTIMATE strength	12,000.0	lb/ft
Geosynthetic in AXIAL direction:		
Tensile force at WORKING conditions	2,384.0	lb/ft
Required ULTIMATE strength	9,297.0	lb/ft
Maximum height of tube, H	12.9	ft
Maximum width of tube, W (at height 4.5 ft from base)	34.0	ft
Ratio H/W	0.381	
Width of base of tube	25.3	ft
Cross-sectional area of lower layer of slurry	228.8	ft^2
Cross-sectional area of upper layer of slurry	146.7	ft^2
Net pumping pressure within tube at inlet	0.5	psi

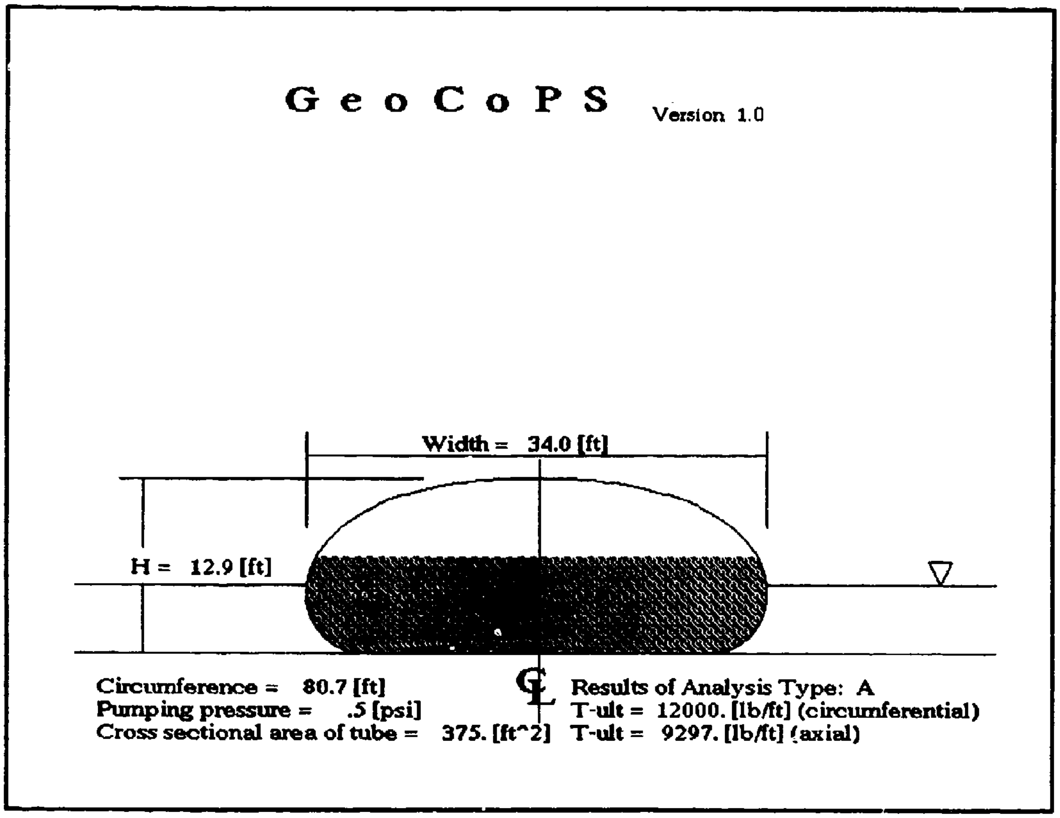

Figure 16. Cross-sectional view: Example 1

GeoCoPS

Version 1.0

Geosynthetic Confined Pressurized Slurry

Project Title:	Example 2
Project Number:	N/A
Project Designer:	N/A
Description:	Given the circumference of the tube and its desired height, find the geometry of the tube, the pumping pressure, and the required strength of the geosynthetic.

Input File Name:	EXAMPLE2.IN
Output File Name:	EXAMPLE2.OUT
Date:	08/27/95
Time:	14:29:00

Page 1 of 1

Input data file: EXAMPLE2.IN Date printed: 08/27/95 Time printed: 14:29:00

G e o C o P S Version 1.0

Geosynthetic Confined Pressurized Slurry

Project title:	Example 2
Project No.:	N/A
Project designer:	N/A
Project description:	Given the circumference of the tube and its desired height, find the geometry of the tube, the pumping pressure, and the required strength of the geosynthetic.

D A T A

Density of Slurry/Density of Water:	1. Lower layer . . .	1.2	
	2. Upper layer . . .	1.2	
Density of outside liquid/Density of Water:	1. Lower layer . . .	0.0	
	2. Upper layer . . .	0.0	
Specified height of lower layer of slurry, Hin-L		10.0	ft
Specified height of outside lower layer of liquid, Hout-L		0.0	ft
Specified safety factors for geosynthetic:			
1. Installation damage, Fs-id		1.3	
2. Chemical degradation, Fs-ch		1.0	
3. Biological degradation, Fs-bd		1.0	
4. Creep, Fs-cr		1.5	
5. Seam strength, Fs-ss		2.0	

Requested type of analysis: 'B' - solve the problem for a circumference of 30.0 ft and maximum desire height of tube of 8.0 ft

R E S U L T S

Results are for a solution converging to a circumference of tube of 30.6 ft and maximum tube height of 7.9 ft

Geosynthetic in CIRCUMFERENTIAL direction:		
Tensile force at WORKING conditions	3,375.0	lb/ft
Required ULTIMATE strength	13,162.0	lb/ft
Geosynthetic in AXIAL direction:		
Tensile force at WORKING conditions	1,960.0	lb/ft
Required ULTIMATE strength	7,643.0	lb/ft
Maximum height of tube, H	7.9	ft
Maximum width of tube, W	10.9	ft
(at height 3.3 ft from base)		
Ratio H/W	0.731	
Width of base of tube	4.7	ft
Cross-sectional area of lower layer of slurry	71.0	ft^2
Cross-sectional area of upper layer of slurry	0.0	ft^2
Net pumping pressure within tube at inlet	3.7	psi

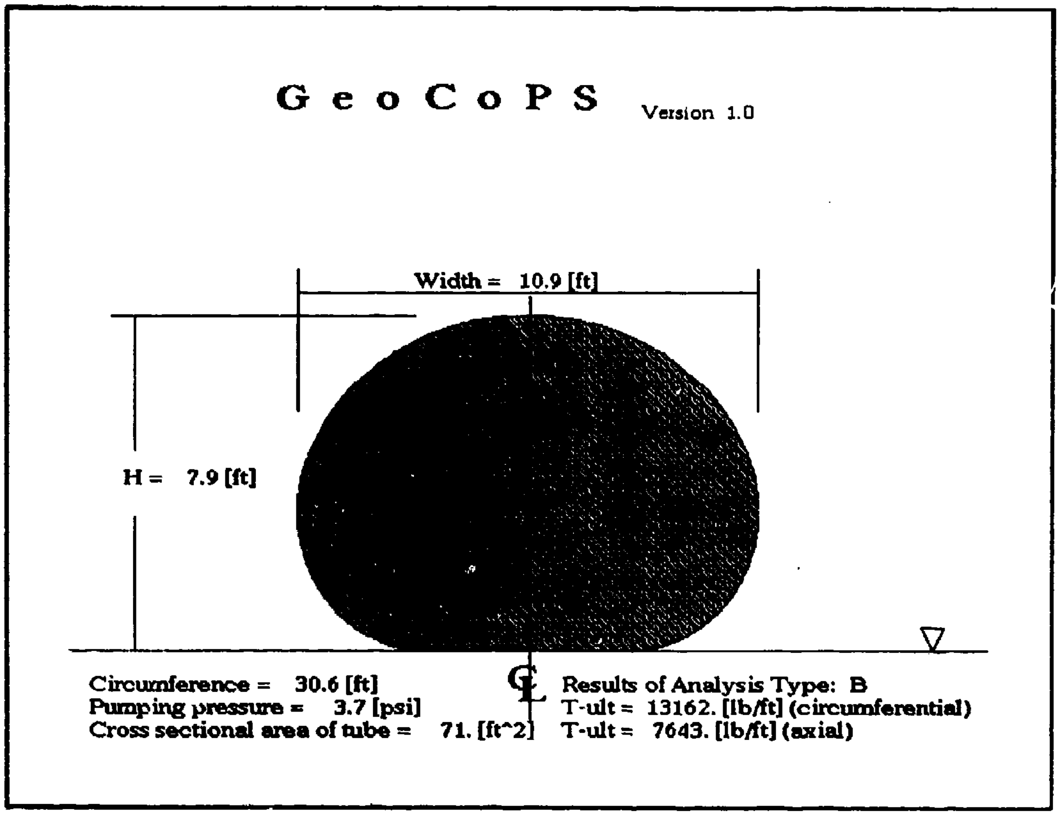

Figure 17. Cross-sectional view: Example 2

anisotropic geosynthetic; such geosynthetics are readily available. The required pumping head is about 7 ft (3.7 psi).

Finally, Example 3 is for a case where the circumference of the tube and the pumping pressure are given as 16.0 ft and 5.2 psi; the results converged to 16.2 ft and 5.2 psi. As in Example 2, one type of slurry and no water outside the tube were specified; however, the slurry density has been increased. See Figure 18 for the calculated cross-sectional view. Once again, the results indicate that an anisotropic geosynthetic for this problem is possibly most economical. Comparing Examples 2 and 3, one sees that cutting the circumference by about 50 percent will decrease the area of the tube (i.e., storage capacity) by about 70 percent. It should be pointed out that in running the analysis option utilized in Example 3, the user is always limited to one type of slurry and either total submergence in water or no submergence at all.

GeoCoPS

Version 1.0

Geosynthetic Confined Pressurized Slurry

Project Title:	Example 3
Project Number:	N/A
Project Designer:	N/A
Description:	Given the circumference of the tube and the pumping pressure, find the geometry of the tube and the required geosynthetic strength in the circumferential and axial dir.

Input File Name:	EXAMPLE3.IN
Output File Name:	EXAMPLE3.OUT
Date:	08/27/95
Time:	14:30:18

Input data file: EXAMPLE3.IN   Date printed: 08/27/95   Time printed: 14:30:18

GeoCoPS   Version 1.0
Geosynthetic Confined Pressurized Slurry

Project title:	Example 3
Project No.:	N/A
Project designer:	N/A
Project description:	Given the circumference of the tube and the pumping pressure, find the geometry of the tube and the required geosynthetic strength in the circumferential and axial dir.

DATA

Density of Slurry/Density of Water:	1.4	
Density of outside liquid/Density of Water:	0.0	
Specified height of lower layer of slurry, Hin-L	5.0	ft
Specified height of outside lower layer of liquid, Hout-L	0.0	ft
Specified safety factors for geosynthetic:		
1. Installation damage, Fs-id	1.3	
2. Chemical degradation, Fs-ch	1.0	
3. Biological degradation, Fs-bd	1.0	
4. Creep, Fs-cr	1.5	
5. Seam strength, Fs-ss	2.0	

Requested type of analysis: 'C' - solve the problem for a circumference of 16.0 ft and net pumping pressure of 5.2 psi at inlet.

RESULTS

Results are for a solution converging to a circumference of tube of 16.2 ft and pumping pressure of 5.2 psi

Geosynthetic in CIRCUMFERENTIAL direction:		
Tensile force at WORKING conditions	2,185.0	lb/ft
Required ULTIMATE strength	8,522.0	lb/ft
Geosynthetic in AXIAL direction:		
Tensile force at WORKING conditions	1,214.0	lb/ft
Required ULTIMATE strength	4,735.0	lb/ft
Maximum height of tube, H	4.6	ft
Maximum width of tube, W	5.5	ft
(at height 2.1 ft from base)		
Ratio H/W	0.839	
Width of base of tube	1.6	ft
Cross-sectional area of slurry	20.4	ft^2

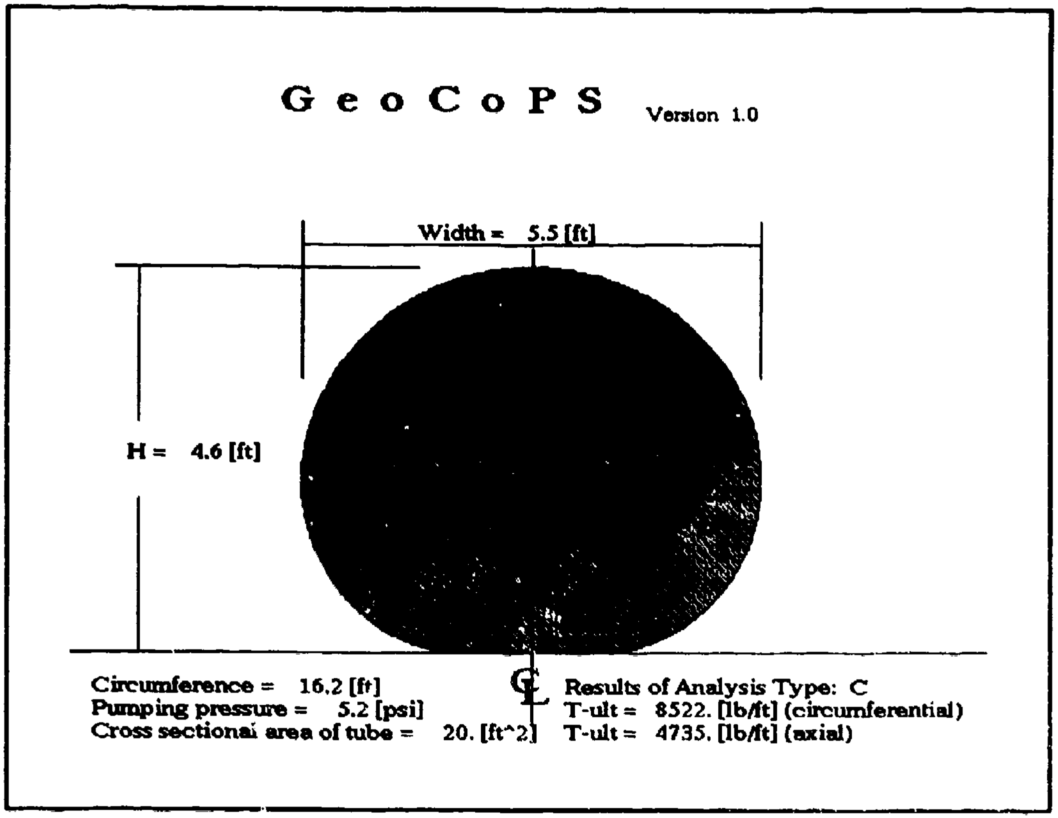

Figure 18. Cross-sectional view: Example 3

7 Conclusion

An overview of analysis to calculate the geometry and stresses of a geosynthetic encapsulating pressurized slurry has been presented. The validity of the numerical procedure utilized to solve the resulting equations has been verified against numerical and experimental results obtained by other investigators.

Parametric studies indicate that stresses in the encapsulating geosynthetic are very sensitive to the pumping pressure. Consequently, during construction it is extremely important to safeguard against an accidental increase in the slurry pumping pressure. The parametric studies also reveal that a significant increase in pumping pressure will only slightly increase the tube's cross-sectional area and, hence, its storage capacity.

A guide to selecting a geosynthetic is provided. It is based on partial safety factors. These safety factors address the seam strength (i.e., the "weak link"), potential installation damage (i.e., accidental increase in pumping pressure), treachery creep, and possible chemical and biological degradation. Also addressed is the required permeability of the geosynthetic so as to perform as a filter; i.e., drain the fluid while retaining the solid particles. Finally, a simple procedure to assess the final height of a tube filled with clayey slurry is proposed.

It should be pointed out that the complete design of geosynthetic tubes has also to include the head loss occurring as the slurry flows away from the inlet. This aspect of design, which will determine either the maximum length of a tube or the distance between inlets along the tube, has not been addressed. Though empirical rules dealing with this aspect exist, a rational analytical procedure is needed.

GeoCoPs (version 1.0) is a tool that will assist in the selection of geosynthetic products for use in dredged material containment systems. As such, this design model will be referenced in the final guidance document. Copies of this report and the accompanying software will be provided to interested users upon request.

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Tubes in the context of this report are made of several geosynthetic sheets sewn together to form a shell capable of encapsulating slurry. The slurry is sufficiently fluid so that it is possible to hydraulically fill the tube. After the slurry is pumped in, the geosynthetic shell acts as a "cheesecloth," allowing the liquid to seep out while retaining the solid particles. The availability of a wide selection of geosynthetics in terms of strength, durability, and permeability enables the use of hydraulically filled tubes in many applications, some of which may be considered critical (e.g., encapsulating contaminated soil). This report presents an overview of an analysis to calculate both stresses in the geosynthetic and geometry of the tube. It also verifies the correctness and validity of the results obtained from a computer program developed to solve the problem. An instructive parametric study implies that the most critical factor needed to ensure successful construction is the pumping pressure; a slight accidental increase in this pressure may result in a very significant stress increase in the encapsulating geosynthetic. Pressure increase, however, has little influence on the storage capacity of the tube. Guidance in selecting an adequate geosynthetic, including partial safety factors and permeability, is also presented. Design aspects associated with the required spacing of inlets and head loss of the slurry as it flows through the tube are considered outside the scope of this report.

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